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# Review of concrete solutions for concrete's environmental impacts

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## Abstract

The use of concrete is under scrutiny as it appears as one of the few human activities where the transition toward a post-carbon society is not possible unless large investments in risky carbon capture and storage are made. With current urbanization, it is also a sector that is expected to continuously grow, leading to increased resource consumption and emissions. In this review, we aim to shed light on the available solutions that can be implemented in the short and long term to reduce greenhouse gas emissions. Rather than waiting for disruptive technologies that could transform a very slow moving and risk-averse construction sector, this review focuses on the small improvements that every stakeholder involved along the value chain of concrete production and use can achieve. We stress how significant the combined effect of these marginal gains can be. By balancing societal needs, environmental requirements, and technical feasibility, the intention of this review is to show credible pathways for a transition to sustainable use of concrete.

## Key points

- Cement usage is so massive, more than 4 billion tonnes per year worldwide, that large-scale replacement by other materials within the next decade is not possible.
- Environmental impact of cement and concrete is low per unit of material, but the amount used makes the impact of the sector highly significant.
- Reductions in CO<sub>2</sub> emissions are possible through successive improvement all along the cement and concrete value chain: less clinker in cement, less cement in concrete, less concrete in structures, and less replacement of structures.
- By engaging all stakeholders of the construction sector, immediate savings of the order of 50% can be reached without heavy investment in new industrial infrastructure or modification of standards.
- Research and development need urgently to be conducted for post-2050 construction to meet future emissions reduction targets. Alternative cement and faster carbonation of concrete should be explored.

## 1 Introduction

Concrete is the fundamental building block of our urbanizing world. It makes up the buildings and infrastructure that enable businesses to operate and people to carry out their daily activities. Over the past centuries, concrete has laid the foundation of the industrialized society<sup>1</sup>. Infrastructure, such as

45 transportation, electric power systems, water and wastewater systems, buildings from single-floor  
46 houses to high-rise buildings – even those with steel or timber frames - all rely on concrete.

47 Concrete is a synthetic rock made of cement, sand, gravel and water, and is by far the most used man-  
48 made material. Cement, which is the mineral glue that sticks together sand and gravel in the concrete,  
49 represents around 10% of concrete mass and is currently produced at around 4 Gt/year, almost the  
50 same amount as food <sup>2</sup>. Over the past 65 years, its consumption increased ten-fold <sup>3</sup>. In comparison  
51 steel production has been increased by a factor 3 and timber construction stayed nearly constant <sup>3</sup>.  
52 Among materials used for construction, cement accounted for 36% of the 7.7 GtCO<sub>2</sub> released globally  
53 in 2010 by construction activities <sup>4</sup>, while steel accounts for 25% <sup>5</sup>, plastics 8% <sup>4</sup>, aluminum less than  
54 4%, <sup>6</sup> and brick less than 1% <sup>7,8</sup>.

55 Concrete accumulates in the Earth's crust and is now considered to be one of the markers of the  
56 Anthropocene <sup>9</sup> with an estimated 900 Gt added since the beginning of the industrial revolution <sup>9,10</sup>.  
57 But it is important to remember that only about half of cement is used for concrete <sup>11</sup>, the rest being  
58 used for blocks, mortars, and plasters. To grasp what volume these masses represent, one should  
59 picture every person on Earth building every year the equivalent of a 20 cm thick concrete wall of 4.5  
60 m<sup>2</sup> area, as well as plastering a wall surface of 35 m<sup>2</sup> with a 3 cm thick cement-based plaster  
61 (considering 300 kg cement/m<sup>3</sup> of concrete and 250 kg/m<sup>3</sup> for cement plaster).

62 By 2050, urbanization is expected to add 2.5 billion people to the global urban population, mainly in  
63 Asia and Africa <sup>12</sup>. Together with the pressure to fill the already sizable housing deficit and lack of  
64 reliably functioning infrastructure, it is anticipated that this population growth will cause a surge in  
65 demand for building materials, including concrete. After 2050, one can expect a reduction of  
66 construction demand in most regions of the world<sup>13</sup> due to the achievement of urban transition and  
67 the stabilization of the population <sup>13</sup>.

68 It is therefore crucial to act now and drastically reduce the environmental impact of construction  
69 within the next decades during this urbanization peak. The new buildings are expected to consume  
70 less energy during their operation, which should increase the focus on emissions related to concrete  
71 <sup>14</sup>. Actually, for a new typical masonry multifamily building type, steel-reinforced concrete represents  
72 50% of the CO<sub>2</sub> emissions attributed to the building, followed by windows, insulation, ceramic tiles,  
73 and paint<sup>15</sup> (**figure 1**). Greenhouse gas (GHG) emissions <sup>17</sup>, local scarcity of non-renewable resources  
74 <sup>18</sup>, energy consumption <sup>11</sup>, water use <sup>19</sup>, dust and particulate matter emissions <sup>20</sup>, mercury emissions <sup>21</sup>  
75 are known issues related with cement and concrete production. But no other known material has been  
76 found to provide the same amount of service than reinforced concrete at such a low economic cost <sup>11</sup>.  
77 Considering the tremendous volume used, unique properties and simplicity of use, its replacement  
78 seems not to be feasible in a decade <sup>16</sup>. As a result, it is vital to develop solutions to mitigate the  
79 environmental impacts of concrete production, while maintaining the favorable properties of concrete  
80 and in the face of increasing global demand.

81 In this paper, we first review the different environmental impacts of cement and concrete production,  
82 use, and disposal. We then look at potential routes for improvement pointing out what can be  
83 implemented within the next decade and what needs to be considered in a longer term. This leads to  
84 policy and stakeholder actions that could pave the way toward a decarbonized construction sector.

85

## 86 2 Cement and concrete environmental impact

87 Environmental impacts related to the production of a material used in such vast amounts are  
88 inevitable. Issues related to resource depletion and global change attract a large attention<sup>22</sup>, but other  
89 issues related to local health aspects have also recently been pointed out <sup>23</sup>. In this section we will step

90 through the different environmental issues related to cement and concrete production, and show that  
91 for most of them implementation of stringent and effective regulation would solve most of the  
92 problems, except for climate change, where technological breakthroughs are needed.

## 94 2.1 Cement and concrete production

95  
96 Portland cement is composed of four major oxides: CaO, SiO<sub>2</sub>, Al<sub>2</sub>O<sub>3</sub> and Fe<sub>2</sub>O<sub>3</sub> coming from raw  
97 materials, usually limestone, clay, and small amounts of "corrective" materials such as iron ore,  
98 bauxite, and sand to reach the desired chemical composition. Raw materials are crushed, mixed and  
99 milled into a raw meal, which is then heated in the pre-heating system to dissociate carbonate into  
100 calcium oxide and carbon dioxide (**Figure 2**). The meal is then calcined in a rotary kiln at up to 1500°C  
101 where reactions between calcium oxide and other elements produce calcium silicates and aluminates  
102 <sup>24-26</sup>. The melted material is then cooled rapidly to form an assemblage of C<sub>3</sub>S, C<sub>2</sub>S, C<sub>3</sub>A and C<sub>4</sub>AF, called  
103 clinker. This clinker is inter-ground with gypsum to a finer product called cement. Concrete is produced  
104 by mixing cement with sand, gravel (or crushed stone), water, and chemical admixtures. It is produced  
105 in a concrete plant and transported by concrete truck to the construction site, or directly mixed at the  
106 construction site. Concrete is also used to produce precast elements. Finally, cement can be used in  
107 plaster and mortar when mixed with water, sand, lime and chemical admixtures, both on site and in  
108 premix mortar factories.

## 109 2.2 Local health issues

110  
111 GHG emissions from cement production have grown to prominence in environmental sustainability  
112 discussions. However, based on the economic valuation of damages caused by air pollutant emissions  
113 and GHG emissions, respectively, recent studies have indicated that the economic burden of resulting  
114 health damages could rival the climate damages from cement production <sup>23</sup>, in particular when  
115 considering particulate matter.

116 The inhalation of small particles, PM<sub>2.5</sub> and PM<sub>10</sub>, is recognized to have significant consequences on  
117 human health - notably linked to respiratory infection, pulmonary disease, lung cancer, heart attacks,  
118 among other diseases <sup>27</sup>. In the production of cement and cement-based materials, the emissions of  
119 PM come from various processes, primarily from material-derived particulates from acquisition,  
120 storage, and handling <sup>23</sup>. Additionally, secondary PM formed from nitrogen oxide and sulfur oxide  
121 emissions associated with the high thermal energy demand and fuels used in cement kilns can further  
122 contribute to health burdens<sup>23</sup>.

123 Currently, appropriate filtering and capture of PM can mitigate many of these emissions from cement  
124 production. Modern electrostatic precipitators and baghouses significantly reduce PM emissions <sup>28</sup>.  
125 For example, cement kiln dust can be captured to a great extent and reused in the production of more  
126 clinker if it has appropriate alkali content, thus reducing emissions <sup>29</sup>. Further, use of scrubbers or  
127 alterations in energy mixes can drive down both PM and other air emissions. Yet regulations requiring  
128 use of such technologies vary by region. For instance, a recent study in Zambia showed that PM<sub>2.5</sub>  
129 concentrations were still 5 to 10 times higher within the vicinity of the cement plant than 1 km away  
130 and respiratory symptoms were 3 times higher <sup>30</sup>.

131 The emissions of PM from cement and concrete production are clearly areas in which appropriate  
132 policy can drive down undesired environmental burdens <sup>17</sup>. Aggregate production, ready mix  
133 operation, construction and demolition generate additional dust which are more difficult to control.

## 134 2.3 Regional resource scarcity

136 To supply the equivalent of 4.5 m<sup>2</sup> of typical concrete wall and 35 m<sup>2</sup> of cement plaster per capita and  
137 per year, more than one ton of gravel, 2.5 tons of sand and 550 kg of cement are required. At the  
138 global level, this demand translates to the direct use of 5.4 Gt of limestone for clinker and filler  
139 production and 17.5 Gt of aggregate, to produce annually approximately 10 billion m<sup>3</sup> of concrete<sup>31</sup>.

140 This tremendous demand for resources has led to a growing concern about potential contributions to  
141 regional resource scarcity for concrete production<sup>32</sup>. In the United States from 1900 to 2000, a period  
142 of significant infrastructure development in the nation, the demand for crushed stone, sand, and gravel  
143 grew from being ~60% greater to being ~290% times greater than the sum of all other raw material  
144 flows used by human activities in that same time period<sup>33</sup>. Although sand and gravel are widely  
145 abundant on Earth<sup>34</sup>, they are usually not transported over long distances due to the economic cost  
146 of transporting such heavy materials<sup>35,36</sup>. Therefore, a construction boom increases the local pressure  
147 for natural sand and coarse aggregates close to urban areas<sup>18</sup>. But as quarries and sand mines become  
148 undesirable due to NIMBYism or too expensive to operate close to urban areas, transportation  
149 distances will increase. For example, aggregates for San Francisco Bay Area (California) come from  
150 British Columbia (Canada).

151 Uncontrolled aggregate extraction damages ecosystems, thus biodiversity, and has potential cascading  
152 affects that impact human wellbeing<sup>37-39</sup>. But these environmental damages are primarily a result of  
153 poor resource management<sup>40</sup> as natural sand extraction usually does not require complex operations  
154 and can be carried on as informal activity near large cities<sup>41</sup>. Thus, quantification of sustainable  
155 resource extraction possibilities around cities should focus on additional factors other than local  
156 availability, such as land use changes<sup>42</sup>, resource accessibility<sup>43</sup> and consideration of political and  
157 economic actions<sup>44</sup>. While local pressures on resources have been noted, it is possible to reduce the  
158 impact of concrete production on ecosystems by using secondary or non-depleted bulk local resources.  
159 An untapped resource in urban context is the excavation material<sup>45</sup>. Each new construction generates  
160 excavation materials usually landfilled outside the city. In Switzerland it represents a similar amount  
161 as the primary material required to build<sup>46</sup>. In China, considering 0.9 t excavation per m<sup>2</sup> built<sup>47</sup>, this  
162 material could currently supply half of the construction material requirement<sup>48</sup>. A better use of this  
163 material is possible through washing to extract sand and gravel from it<sup>49</sup> or directly through clay based  
164 concrete<sup>50</sup>. Finally, sustainable resource management can be achieved through promotion of strong  
165 policy and regulatory frameworks, such as certification systems to secure the good practice along the  
166 supply chain (e.g., CSC label<sup>51</sup>).

167

## 168 2.4 Global environmental issues

169 One of the most commonly discussed environmental impacts related to cement production is the high  
170 level of GHG emissions. Among materials used for construction, cement accounts for 36% of emissions  
171 related to construction activities<sup>4</sup> and 8% of total anthropogenic CO<sub>2</sub> emissions<sup>52</sup>. At least 70% of the  
172 GHG emissions from concrete production is due to cement production (**Figure 1**)<sup>31</sup>. Unlike regional  
173 resource scarcity and local health issues, for which in many cases there are mitigation strategies that  
174 can be implemented today, technological breakthroughs are needed globally to meet GHG emissions  
175 mitigation goals.

176 Within cement manufacturing, the predominant source of emissions is the kilning stage; grinding,  
177 sorting of raw materials, and packaging of cement bags have minor impacts<sup>17,53</sup>. Most of the emissions  
178 are from the decomposition of limestone (calcination) and associated with energy use<sup>54</sup>. Energy-  
179 derived emissions can be notably reduced through kiln efficiency and choosing lower-carbon fuels<sup>55</sup>.  
180 Current average cement production emits approximately 0.31 kg of CO<sub>2</sub> per kg of cement from energy-  
181 resource combustion<sup>56</sup>. Calcination represents around two-thirds of the total GHG emissions from  
182 cement produced using a state of the art dry process rotary kiln equipped with pre-calciner<sup>57</sup>. These  
183 are the main reasons why cement production is considered to be difficult to decarbonize<sup>16</sup> as

184 decarbonization of the energy supply will not eliminate the material-related CO<sub>2</sub> emissions from  
185 calcination<sup>16</sup>. However, there have been many mitigation strategies for these emissions, several of  
186 which are discussed in the subsequent sections.

187 As a consequence of the annual demand for 4.5 m<sup>2</sup> of concrete and 35 m<sup>2</sup> of plaster for every inhabitant  
188 on the planet, there is an associated ~300 kg CO<sub>2</sub> of cement-related emissions per capita. For context,  
189 this would be approximately 3 times less than a return flight between London and New York city. While  
190 concrete's societal benefits are undeniably very important, GHG emissions are a real problem for the  
191 cement and concrete industries - and for the World.

192

### 193 3 Credible medium-term solutions to reduce cement demand

194 The peak in new construction will come in the next few decades, so it is most important to focus on  
195 reductions in environmental impact that can be achieved in the medium term, before 2050. The  
196 substantial reduction needed can only be achieved by considering efficiency at all stages of the value  
197 chain: clinker production, cement production, cement use in concrete or mortar, concrete use in  
198 construction, design of structures and use of structures. It is essential that all parts of this chain are  
199 considered as there is no point saving, for example, 30% CO<sub>2</sub> in cement production and then using  
200 twice as much cement as needed in the concrete. In this section, we explore the potential for further  
201 reductions in environmental impacts along this value chain (**Table 1**). These solutions are of particular  
202 importance because they can often be implemented without new production technologies or  
203 infrastructure.

204

#### 205 3.1 Efficiency of clinker production

206 As previously described the majority of CO<sub>2</sub> emissions in concrete, come from clinker production.  
207 Driven by the huge increase in energy costs associated with the oil crisis of the 1970s, there has been  
208 considerable progress in the energy efficiency of clinker production. Globally over 85% of cement kilns  
209 use energy-efficient dry methods, which do not need additional energy to evaporate water<sup>58,59</sup>. There  
210 has also been substantial progress in heat recovery and recycling (**Figure 2**). State-of-the-art kilns  
211 achieve about 63% efficiency and through integrated approaches could reach 80% efficiency<sup>60</sup>. Such  
212 levels of efficiency make modern kilns among today's most efficient thermal machine in wide-scale  
213 industrial use. There is therefore limited scope for further improvement<sup>55</sup>.

214 Modern cement kilns are also extremely flexible in terms of fuel source and many plants in Europe use  
215 various waste streams for more than 80% of the energy demand. In 2013 in Europe, around 1.3 million  
216 tyres (50% of total recycled tyres) were used as fuels for clinker production. Already in the 1990s in  
217 the United States, about 70% of all hazardous wastes were burnt in cement kilns. Waste materials  
218 derived from fossil fuels such as solvent, plastics, tyres are not regarded as carbon neutral. However,  
219 it is important to note that transferring waste fuels from incineration plants to cement kilns results in  
220 a significant net CO<sub>2</sub> reduction because cement kilns are more efficient<sup>61</sup>. Another advantage is that  
221 no toxic residues such as dioxins are generated since the ashes are completely incorporated in  
222 clinker<sup>62</sup>. The International Energy Agency Roadmap expected the worldwide use of "alternative fuels"  
223 to grow from 3% in 2006 to about 37% in 2050 and deliver around 15% of the targeted overall  
224 reduction in CO<sub>2</sub> emissions<sup>55,63</sup>.

225 This increase in fuel efficiency means that fuel now accounts for only about one-third of the CO<sub>2</sub>  
226 emissions from clinker production. It is much more difficult to reduce the other two-thirds coming

227 from the decomposition of limestone, which is related directly to the chemical composition of the  
228 clinker, namely the content of calcium oxide.

229 Given the difficulty of producing materials with substantially lower contents of CaO, it could be  
230 considered if there are sources of CaO other than limestone (CaCO<sub>3</sub>). Unfortunately, practical sources  
231 of non-carbonate calcium are quite limited. The fine material left from crushing concrete for recycling  
232 aggregate is one potential source, which is just starting to be exploited. But in countries where most  
233 of construction will occur, the volume of new construction will far outstrip the volume of demolition.  
234

### 235 **3.2 Efficiency of cement production**

236 By far the most promising route to large scale reduction in GHG emissions comes from substituting in  
237 the cement, as much clinker as possible by other materials, collectively known as SCMs (supplementary  
238 cementitious materials). This is a strategy already widely adopted. The most widely used SCM is fine  
239 limestone – the same as the raw material used to produce clinker, but as this is just ground, rather  
240 than being heated to high temperature it does not lose its CO<sub>2</sub> and has very low associated emissions  
241 <sup>64</sup>. Although this material is widely available, it has very limited reactivity and at levels of substitution  
242 above around 10-15% it is simply a filler <sup>65</sup>.

243 The next two most used SCMs are fly ash and blast furnace slags, which are respectively by-products  
244 from coal power plants and iron industry <sup>66</sup>. While very valuable in decreasing environmental impact  
245 today <sup>67</sup>, they amount to only 15% of current cement production and almost all sources are already  
246 used either in cement or later added to concrete. Furthermore, this amount is likely to decrease in the  
247 future, as we move away from using coal and more steel is recycled.

248 However, there is great potential for large scale CO<sub>2</sub> reductions through more extensive use of clays,  
249 which are very widely available worldwide and which when calcined (heated) to relatively modest  
250 temperatures can give a highly reactive SCM <sup>68,69</sup>. The substitution of clinker by a combination of  
251 calcined clay and limestone gives cements (so-called LC3) with good levels of performance, even at  
252 high substitution levels <sup>64,70,71</sup>. If clinker substitution is not limited by the availability of SCMs, as is the  
253 case for using calcined clays it can be estimated that overall CO<sub>2</sub> savings of 15-30% of current levels  
254 from cement, can be achieved worldwide.

255

### 256 **3.3 Concrete efficiency**

257 There is considerable scope to reduce CO<sub>2</sub> emissions by a more efficient use of cement in concrete  
258 through better mixture design. Studies show that for the same performance we can have a factor 3 of  
259 variation in cement content per cubic meter <sup>72,73</sup>. This variation is the result of different production  
260 technologies and lack of knowledge. Mixture proportions can be selected to meet necessary properties  
261 while reducing GHG emissions <sup>74</sup>. In general, manual mixing on site from cement in bags is the most  
262 inefficient. More efficient mixing in a concrete truck, or better still a ready mix plant, can reduce the  
263 cement content for the same properties by a factor of 2 <sup>75</sup>. The use of a proper mixture design in a  
264 concrete plant, with appropriate proportion of sand, gravel can lead to further reductions (up to 50%)  
265 without loss of strength or fluidity <sup>76</sup>. Such improvements are an untapped potential in emerging  
266 countries where most of the cement is sold in bags and used without proper technical control or mix  
267 design optimization <sup>77</sup>. Promoting industrialized concrete production as a replacement for site-mixing,  
268 especially in self-help housing schemes is a very effective way to reduce cement consumption in both  
269 concrete and mortar applications<sup>78</sup>.

270 Concrete efficiency can be taken even further by engineering in such way that up to 60% of the cement  
271 can be replaced by fillers – simple ground material – in combination with dispersant admixture. This is

272 an emerging technology that has been shown to be feasible in precast and ready-mix concretes in  
273 Germany<sup>79</sup> and Brazil<sup>80</sup>. It is also feasible in the dry set rendering mortar market<sup>81</sup>. The technology  
274 requires adequate supply chain of fillers and efficient dispersants, advanced knowledge and technical  
275 capability. Limitations are the cost of the dispersant admixture and existing concrete standards.

276

### 277 3.4 Construction efficiency

278 Waste on construction sites represents a largely underestimated amount of material. A large national  
279 study performed in Brazil showed wastage levels as high 50 to 100%<sup>82</sup>. The findings of this study are  
280 especially important and highlighted that waste rates were much higher for the use of cement sold in  
281 bags than for ready-mix. This issue is especially relevant in emerging countries, where the largest  
282 growth in concrete demand is expected and where quality control on construction site may be lower.  
283 Better design and site management practices were found to be important. Further, decisions taken  
284 during construction phase, such as the curing period before demolding concrete, can cause notable  
285 changes in the quantity of cement needed for concrete production<sup>31</sup>. Better control on water and  
286 aggregate humidity on construction site can also have a critical influence<sup>83</sup>. Since waste cost to  
287 builders, raising awareness was efficient on Brazilian market<sup>82</sup>. Education of construction workers is  
288 also a proven strategy<sup>84</sup>.

289

### 290 3.5 Design efficiency

291 Research has shown that buildings use structural material inefficiently<sup>82</sup>. In structural systems, GHG  
292 reduction is complicated by the interplay of concrete performance (and hence mixture proportions)  
293 and the quantity of steel reinforcement, which are often highly constrained by codes. For reinforced  
294 concrete columns, an increase in concrete compressive strength typically leads to a reduction in GHG  
295 emissions, while for reinforced concrete beams, achieving same strength but with lower clinker is the  
296 target<sup>85</sup>. These combined optimization strategies of concrete strength, rebar content and clinker con-  
297 tent can provide around 20% reductions in GHG emissions<sup>85</sup>. Similar reduction can be achieved for  
298 structures where the dead load is the key design parameter through the use of high performance con-  
299 crete<sup>86</sup>. Orr and co-authors demonstrate that more efficient utilization of structural concrete had the  
300 potential to achieve material savings up to 30–40% through design optimization<sup>87</sup>. Although the mag-  
301 nitude of such savings is difficult to quantify, the works of De Wolf<sup>88</sup>, Shank and co-authors<sup>89</sup> would  
302 also argue for 10%-20% reduction within conventional design constraints. Finally, savings can also be  
303 achieved by increasing the time to functional obsolescence of structure and avoiding the need for a  
304 structure to be demolished and rebuilt<sup>90</sup>. This is of particular importance for the existing infrastructure  
305 in Northern countries which have been mainly built in the period 1960-1980, with a planned service  
306 life of 50 years. Innovative solutions with ultra high performance concrete allow extension of the ser-  
307 vice life of infrastructure with less than 50% the GHG emissions required for conventional rehabilita-  
308 tion, and a fraction of what it would cost to rebuild them<sup>91,92</sup>.

309

### 310 3.6 Reduction of GHG emissions all along the value chain

311 It is clear that working on marginal gains all through the value chain can lead to substantial savings in  
312 GHG emissions (**Table 2**). The savings are not necessarily additive and may not be appropriate in all  
313 applications, but Shanks and co-authors show that around 50% of clinker production, in the UK, could  
314 be reduced through combined application of existing technologies<sup>89</sup>. The substitution of cement with  
315 calcined clay and limestone has the biggest potential to reduce GHG emissions. Reducing the amount  
316 of cement in concrete has the next highest potential, followed by floor slab optimization through  
317 prefabrication and post-tensioning (**Table 2**). The difficulty to implement these savings comes mainly  
318 from the fact that the construction sector is a fragmented industry with multiple stakeholders<sup>93</sup>.  
319 Outside the cement industry, which concentrates investment and production capacity, the other  
320 stakeholders from waste management companies to concrete producers or engineering office are



321 often decentralized entities, relying on multiple independent offices <sup>94</sup> (**Table 2**). Without strong  
322 enforcement policy implemented with a top down approach and efforts to integrate the value chain,  
323 the transformation of the construction sector will take time <sup>95,96</sup>.

324

## 325 **4 Necessary long-term development towards zero carbon concrete**

326 After 2050, global society will continue to require infrastructure elements that can only realistically  
327 be constructed from concrete. Combining this with the need to move the sector to carbon neutrality,  
328 and considering the opportunities opened by a longer research and development timescale to  
329 demonstrate in-service performance of radically new material types and design strategy, there is  
330 significant interest in looking beyond established practices to investigate wholly different ways of  
331 producing and using concretes. This section explores the most promising options.

332

### 333 **4.1 Breakthrough solutions, the reality behind the hype.**

334 Abundant technical literature exists regarding possible disruptive technologies as alternative to  
335 cement production<sup>97,98</sup>. According to various authors, such technologies can play an essential role in  
336 the future of the construction sector by replacing cement in part or in full<sup>99</sup>. Several alternative  
337 cements have been shown to be able to contribute to reduced environmental impacts relative to  
338 conventional cements<sup>100,101</sup>. However, the pace of change in the construction industry, issues in  
339 materials availability or cost, and the technical limitations of some of these alternative technologies,  
340 mean that many proposed material alternatives are unrealistic from technical or resource standpoints  
341 and are unlikely to reach large-scale technical maturity before 2050 where a transition to net zero  
342 emissions is required. It is actually difficult for alternative cements to meet more than 5% of the  
343 projected future demand for cementitious materials <sup>102,103</sup>.

344 Even though sufficiently mature alternative cements are already in use at commercial scale in many  
345 parts of the World, the production capacity expansion is limited. For example, calcium sulfo-aluminate  
346 (CSA) cements are well-known products, largely used in China. This technology is a real alternative  
347 compared to Portland cement as it is based on aluminum chemistry avoiding the decarbonation of  
348 limestone <sup>104</sup>. The main issue is lack of high-alumina raw materials, which limits its implementation to  
349 a few percent of cement production at most. Let's imagine that even if all current bauxite production  
350 was diverted from the production of aluminum it would not be sufficient to provide more than 10-15%  
351 of the current demand for cement.

352 But other alternatives could be able to be scaled up in the next 20 years. Alkali-activated cements have  
353 been discussed at some length as a potential alternative to Portland cement in many large-scale  
354 applications<sup>103</sup>. In regions where the supply of both suitable activators and precursors is plentiful, they  
355 have been shown to be economically and technically viable in precast and ready-mixed formats <sup>105</sup>.  
356 However, there remain supply-chain challenges related to availability of highly effective alkaline  
357 activators such as sodium silicate, which are not currently produced at sufficient scale to replace even  
358 a fraction of a percent of global Portland cement production. Work based on alkali-activation using  
359 more widely available salts such as sodium carbonate does show high potential for scalability of  
360 production<sup>106</sup> but is still in competition for the supply of aluminosilicate precursors, as the precursors  
361 are also used as SCMs in Portland cement-based concretes and already facing limited availability.  
362 Nonetheless, alkali-activated concretes have the capacity to integrate in their manufacture high alkali-  
363 content solid wastes which cannot normally be recovered<sup>97,107</sup>.

364 One of the main challenges in the area of alkali-activated concretes, and other technologies based on  
365 industrial wastes, relates to the scale on which waste are needed to become a realistic input into large-

366 scale construction. Waste which is generated at a rate of tens of tons per annum may be a major  
367 disposal challenge for many industries, but this is a scale which is far too small to be worth even  
368 considering for use in commercial-scale construction, unless the material has very specific technical  
369 characteristics that can improve performance of cementitious or concrete materials. Among the  
370 promising wastes available at the scales needed for realistic use in concretes are those which result  
371 from mining operations, biomass combustion, metallurgical recycling and/or modernized extractive  
372 metallurgy, and construction and demolition waste<sup>108</sup>. They all share the characteristic that they can  
373 be to some extent quality-controlled, which is essential to achieve the necessary consistency of  
374 construction products.

375 Magnesium-based cements can be produced based on magnesium carbonates or oxides, replacing  
376 limestone and using various alternatives to the conventional clinkerization process<sup>109</sup>. They can have  
377 a sustainability advantage if magnesium carbonate is obtained through carbonation of geologically-  
378 sourced magnesium silicate by uptake of CO<sub>2</sub> that would otherwise be emitted to the atmosphere<sup>110</sup>.  
379 However, past attempts to develop a scalable process have not succeeded, and the likely very high  
380 capital expenditure requirement makes implementation challenging even considering a 30-50 year  
381 perspective<sup>111</sup>. Furthermore, even if low-energy scalable processes become available for exploiting  
382 magnesium silicates, the availability of these materials is much more localized than limestone used to  
383 produce Portland cements, entailing significant transport costs if cements based on magnesium  
384 silicates are to be used on a global rather than local scale<sup>112</sup>. Moreover, magnesium silicates are less  
385 available near the Earth's surface, so deep mining operations would be required to recover the  
386 amounts needed to meet the demand for construction. Magnesium recovery from brines for use in  
387 cements has also been proposed<sup>113</sup>, but is also probably geographically limited to regions in which  
388 large-scale seawater desalination is taking place or where salt lakes are accessible.

389 Many other suggested solutions are based on the idea of cement setting and hardening through  
390 carbonation of calcium oxide. This allows to capture the CO<sub>2</sub> emitted during cement production and to  
391 tend toward carbon-neutral cement. The problem is to find sources of calcium oxide that do not come  
392 from the decarbonation of limestone in the first place. If CaO is derived from limestone, then there  
393 can be no net gain as the CO<sub>2</sub> which can be reabsorbed can never be higher than the CO<sub>2</sub> emitted in the  
394 decarbonation step, and there would still be additional impacts from required process energy.  
395 Development of "Carbonatable Calcium Silicate Cement" (CCSC) technology has been developed  
396 thanks to recent development to accelerate and control carbonation industrially without excessive  
397 energy consumption<sup>114</sup>. Simple calcium silicate minerals such as wollastonite can carbonate very  
398 rapidly in relatively pure CO<sub>2</sub> gas (e.g., Solidia Cement<sup>115</sup>). These binders are well-suited for the  
399 fabrication of thin precast products, to allow CO<sub>2</sub> and water transfer during curing. They also involve  
400 some capital costs and non-negligible operating costs as well<sup>102</sup>. Finally, wollastonite is, as discussed  
401 above for magnesium silicate, not a well distributed resource in the Earth's crust and can thus only be  
402 a solution for some specific locations. As the current global wollastonite production amount is 500 000  
403 tons per year, mainly in China<sup>116</sup>, a transition towards this technology would require wollastonite  
404 extraction to increase by a factor of around 10 000.

405 There has been much focus on concrete made with alternative cements for over half a century, but  
406 the availability of raw materials, the confidence in long term performance, or the limitation to specific  
407 application in well-controlled environments make it unrealistic to consider any of these alternative as  
408 a direct one-for-one replacement for conventional cementitious materials within the next decades.  
409 However, when considering a more local context, and if it is proposed to move away from the idea  
410 that all locations in the World can (or even should) be using the same type of cement for all  
411 applications, there is a great deal that can be achieved by the production of fit-for-purpose local  
412 cement technologies and solutions specific to the areas where the desired resources do exist. The most  
413 critical issue here is cost; these alternative cements must be made scalable and cost-competitive, but  
414 can only occur at a local level.

415

## 416 4.2 Carbonation of cement and concrete

417 For classic Portland cement, further CO<sub>2</sub> savings can be achieved in the use phase and at end of life.  
418 Actually, when exposed to the atmosphere, cementitious materials can capture CO<sub>2</sub> through  
419 carbonation. The amount taken up is some fraction of the one released by limestone decomposition  
420 (calcination) during cement production.

421 Carbonation involves the calcium-containing phases from cement such as calcium-silicate-hydrates,  
422 calcium-aluminate-hydrates as well as portlandite (Ca(OH)<sub>2</sub>) reacting with CO<sub>2</sub> to produce mainly  
423 calcium carbonate and other non-carbonated phases<sup>117</sup>. The reaction starts on the exposed surface  
424 and proceeds by CO<sub>2</sub> diffusing slowly inwards. This reaction has been extensively studied by engineers  
425 because, by reducing the pH of the concrete pore water below pH ~9.4, it may damage the  
426 electrochemical protection of mild steel reinforcement bars against corrosion<sup>118 123</sup>, which is  
427 deleterious for the durability of concrete structures exposed to high relative humidity or rain.

428 Carbonation depth is commonly described as a diffusion-limited process:  $\text{depth} = k \cdot t^{0.5}$  (where t is time  
429 and k a constant). The value of k for real concrete structures usually varies between 2 and 15 mm/yr<sup>0.5</sup>  
430<sup>119</sup>, meaning that a 200 mm thick concrete column can take 44 to 2500 years to reach pH 9.4. No  
431 systematic information exists on carbonation of other products such as mortars and renders, except  
432 for a mention<sup>120</sup> of unpublished results with k ranging from 6.1 to 36.9 mm/yr<sup>0.5</sup>, the latter suggesting  
433 that a 30 mm layer of mortar will carbonate in merely 8 months!

434 Furthermore, carbonation depth unfortunately does not translate immediately to carbon capture  
435 because reaching pH<9.4 requires only a fraction of the available CaO and MgO to be combined with  
436 CO<sub>2</sub><sup>121</sup>. It is known that this fraction – the degree of carbonation – is maximum at the surface and  
437 decreases inwards (Figure 3)<sup>121</sup>. Capture-focused studies have often assumed a simplified profile  
438 (Figure 3). The maximum carbonation degree, in terms of available CaO converted to CaCO<sub>3</sub>, reported  
439 in these models varies but can be up to 100%<sup>120</sup>. Lower figures appear more realistic, e.g., 50% as a  
440 final carbonation extent for crushed materials<sup>122</sup> or 30-90%<sup>123</sup>. Factors such as porosity, chemical  
441 composition of the hydrates, presence of SCMs, cement paste volume, and environmental conditions  
442 influence the maximum carbonation degree achieved<sup>117</sup>. Therefore, with today's knowledge, there is  
443 large uncertainty in any estimation of the amount of CO<sub>2</sub> that can be captured by a single structure<sup>122</sup>.

444 Nevertheless, a few estimates of CO<sub>2</sub> capture by the in-use stock of cementitious products and waste  
445 have been published<sup>128,129</sup>, with global estimates varying between 0.9 Gt in 2013<sup>120</sup> to 0.7 ±1.2 Gt for  
446 2015<sup>124</sup>. In these global studies, capture is about 25% of the total annual CO<sub>2</sub> emissions from cement  
447 production. Values of 14-19.6% of annual emissions have been published for Portugal<sup>125</sup> and 17% for  
448 Sweden<sup>123</sup>. Further data collection on carbon capture of cementitious materials in current structures  
449 is needed. So far systematic data are limited to a Swedish study<sup>123</sup>. Some initial international efforts  
450 are described in PD CEN/TR 17310:2019<sup>126</sup>, but the methodology of that study requires further  
451 extension and refinement to capture the range of influential parameters described above.

452 However, it is important to understand that this carbon uptake cannot be used to reduce the attributed  
453 current environmental impact of concrete production as this capture has already been happening.  
454 Some companies have started to explore CO<sub>2</sub> mineralization for products used in concrete (e.g.<sup>127</sup>). To  
455 be able to claim for a carbon uptake to count as a carbon sink related to COP21 Paris agreement  
456 targets, one would need to intentionally increase and hasten the carbonation process. This is what we  
457 explore in the following sections.

458

459 Increased CO<sub>2</sub> uptake at end of life

460 At the end of concrete's lifetime when it may be crushed into smaller pieces for reuse as aggregate in  
461 new concrete, carbonation could be increased due to higher surface exposure. This is by far the most  
462 discussed possibility to increase CO<sub>2</sub> uptake during concrete's life cycle. The total potential uptake  
463 could be around 75% of the initial limestone decalcination emissions<sup>122</sup>. This represents about 110 kg  
464 CO<sub>2</sub>/m<sup>3</sup> for average concrete<sup>128</sup>. However, currently crushed concrete is stockpiled into a construction  
465 and demolition heap, and due to limited porosity of the heap itself, the carbonation of the piled  
466 aggregates is actually limited<sup>122</sup>. Afterward, recycled aggregates are reused as road subbase or in new  
467 concrete, which again reduces the carbonation potential due to limited access to CO<sub>2</sub><sup>129</sup>. An increased  
468 carbonation rate could be achieved by longer exposure of crushed aggregates to the air or through  
469 enhanced processing such as accelerated carbonation<sup>130</sup>. However, the volume of materials to handle,  
470 the need to bring back these materials from demolition sites to concentrated industrial treatment  
471 facilities (with associated CO<sub>2</sub>, particulate matter, and noise emissions from both transport and  
472 crushing), as well as the very low price of aggregates in many regions, makes full-scale development  
473 and deployment challenging in the global context.

474

#### 475 Increased CO<sub>2</sub> uptake in the use stage

476 Reinventing industrial practices to increase CO<sub>2</sub> uptake is conceptually feasible since carbonation only  
477 reduces the durability of steel reinforced concrete that is exposed to outdoors wet and dry cycles or  
478 high humidity<sup>118,131</sup>, which is only a fraction of the ~40% of cement going to reinforced concrete<sup>132</sup>.  
479 For all other elements, carbonation is mostly beneficial, including sometimes increased strength and  
480 reduced porosity<sup>117</sup>. More than 80% of cement is used in applications where higher carbonation will  
481 not induce durability concerns<sup>132</sup>. Therefore, engineers could be educated to embrace carbonation  
482 under these circumstances and actually design for carbonation.

483 Cements with a high SCM fraction not only emit less CO<sub>2</sub> during production, but also carbonate  
484 significantly faster and to a higher degree than conventional Portland cement<sup>117,133,134</sup>. In one example,  
485 the carbonation rate is increased by a factor 3 and maximum carbon uptake by a factor 2<sup>135</sup>. As a  
486 consequence, the replacement of current cements with high-SCM cements would, as a first step,  
487 reduce the total amount of CO<sub>2</sub> released into the atmosphere during cement production (due to  
488 reduced clinker content). Then, as carbonation is also faster, it will reduce the time during which the  
489 emitted CO<sub>2</sub> is staying in the atmosphere and the associated additional radiative forcing.

490 Considering the need for CO<sub>2</sub> diffusion to enable carbonation, design changes in terms of geometry  
491 (thickness) and CO<sub>2</sub> permeable surface coverings are also possibilities to reduce the time for capture  
492 and reduce the amount of materials and cement. 3D printing technology can introduce a degree of  
493 freedom making possible not only new shapes – increasing surface/volume ratio<sup>136</sup> - but also to vary  
494 the composition of concrete inside a given component. However, this technology is still in its infancy<sup>137</sup>.

495

#### 496 Carbon Capture and Storage

497 No cement can be neutral in overall CO<sub>2</sub> emissions unless carbon capture and storage (CCS) is used.  
498 Different technologies are available<sup>138</sup> (absorption, membrane process, mineral carbonation, oxyfuel,  
499 and others). Investment cost ranges between 200 and 300 million Euros per kiln<sup>59</sup>, inducing a possible  
500 increase of between 50 to 100% in the price of cement<sup>139</sup>, which can increase social inequalities.  
501 Actually, the increase in total costs for the construction of a middle-class multifamily residential  
502 building is limited to 1%, even when the cement price is doubled<sup>140</sup>. On the contrary, for low cost  
503 housing, the cost of cement represent 5 to 10% of construction costs and a price increase would  
504 directly impact final costs. Finally, legal issues to define which stakeholder will have to carry the risk

505 associated with CO<sub>2</sub> storage is not solved <sup>141,142</sup>. These legal uncertainties are delaying large scale  
506 implementation, although all experts are urging the sector to act fast <sup>143</sup>.

507

## 508 **5 Stakeholder actions for future implementation of sustainable cement and concrete**

509 Concrete: the most destructive material on Earth. This is how this material is presented by some  
510 general media <sup>22</sup>. But housing and infrastructure needs for growing urban population make its use  
511 unavoidable, and its environmental impacts come more from the scale of use rather than its per-unit  
512 contribution. It is hard to blame the material or the technology while the cause is mainly the  
513 urbanization and the massive use of such material. Certainly, concrete allows us to handle the social  
514 challenges of housing and infrastructure demand with a minimum environmental impact per product  
515 delivered. We pointed out that stringent regulation and control can push the widespread  
516 implementation of already-used technologies to reduce environmental and health impacts associated  
517 with material extraction, water consumption, particulate matter, and heavy metals emissions. GHG  
518 emissions and contributions to climate change are the urgent remaining challenges to focus on. It is  
519 accepted by industry as well as public actors that cement and concrete have an environmental burden.  
520 However, there is far less consensus when dealing with action to remediate to this situation.

521 Depending on the efficiency of the cement plant and the amount of waste co-processed, a same  
522 product coming from two different cement plants will have very different environmental impacts <sup>144</sup>.  
523 More transparency and better measurement could help the various stakeholders to make informed  
524 choices. In this perspective, the Concrete Sustainability Council (CSC) is a recent initiative from the  
525 cement and concrete industry to follow the Forest Stewardship Council (FSC), which awards  
526 certification that a finished concrete product can fulfil sustainability criteria along the upstream value  
527 chain up to the cement plant. This includes environmental and social issues such as land use, air quality,  
528 water, biodiversity, health and safety, labor practices<sup>51</sup>.

529 Concrete is also typically seen a single material, but the diversity of cement types and concrete mixes  
530 makes it such that for similar strength and durability performance one can triple the carbon footprint  
531 of the product<sup>72,145</sup>. As long as specifications are based on material formulations or recipes (which is  
532 currently the most popular approach in standards worldwide), or even on technical performance  
533 (strength, fluidity) and not on environmental performance, there will be no incentive from the  
534 concrete producer to propose an environmentally friendly mix design. Some concrete producers have  
535 started to guarantee to their customers that they will provide a given class of low carbon concrete (15,  
536 25 and 40% lower CO<sub>2</sub> than average standard) at a construction site (e.g., Vertua<sup>146</sup>). This is a clear step  
537 forward and shows a change taking place in the profession. Moving standards from a recipe  
538 (prescriptive) basis to a performance basis is essential, but demands that “performance” is defined  
539 holistically and including environmental considerations if it is to have the necessary effect on emissions  
540 across the sector.

541 At the structural level, one can observe the same misunderstanding. It is possible to design materially  
542 efficient structures, but clients usually do not ask for it <sup>147</sup> and without a request from the client (or a  
543 national or regional policy requiring that this be done), the design team has no incentive to optimize  
544 their structure and will go for very regular 20 cm thick slabs.

545 Efforts from all stakeholders, from policymakers downwards, are therefore required to accumulate all  
546 marginal gains available (**Table 2**). However, time constraints, fragmented supply chains, and lack of  
547 awareness are some of the many barriers for implementation. In order to motivate all the different  
548 actors involved in cement use, a set of benchmarks can be proposed <sup>111</sup>. In Europe, it was proposed to  
549 use for the cement producers, the tCO<sub>2</sub>/t<sub>clinker</sub> metric, which should be lower than 0.7 <sup>55</sup>. Concrete  
550 producers should achieve less than 3.5 kg clinker/m<sup>3</sup>/MPa for a standard concrete mix (30-50 MPa) <sup>72</sup>.

551 Engineering offices that design concrete structures should achieve less than 250 kg CO<sub>2</sub>/m<sup>2</sup> floor area  
552 for the concrete allocated to the structure<sup>88</sup> and prescribe exposure class with no corrosion risk when  
553 concrete is used indoors. For construction companies, less than 500 kg CO<sub>2</sub>/m<sup>2</sup> floor area for the whole  
554 building is a good benchmark<sup>148</sup>. These are European benchmark propositions and they need to be  
555 tailored to the local context. In particular, they become highly irrelevant when looking at the informal  
556 concrete production sector<sup>83</sup>, which represents a non-negligible part of cement consumption.

557 Carbonation should be taken as an opportunity. Thanks to the current movement toward using  
558 cements with high amounts of clinker substitution, we can design for faster carbonation and shorten  
559 considerably the carbon overshoot due to urbanization. As long as concrete is not directly exposed to  
560 90% relative humidity and construction details are finished with high quality, there will be no durability  
561 issue. Innovative corrosion resistant steel alloy may also solve this problem

562 No single “silver bullet” innovation will achieve sustainable cement use and cement industry will not  
563 solve all problems acting in isolation. It is part of a loosely coupled and complex network of actors that  
564 collaborate to produce buildings and infrastructure<sup>93</sup>, from the material producer, the engineering  
565 office, the architect, the construction manager, the policy maker and the owner of the future building.  
566 And it is the collaboration between actors that produces significant differences<sup>149</sup>. Like in sport, it is  
567 the combination of marginal gains which actually makes the difference<sup>150,151</sup>.

568

569

570

571  
572

**Box 1: Heavy metals and hazardous substances emissions**

573 Emissions during cement production

574 The fuels and raw materials used in cement kilns can be sources of hazardous air pollutant emissions  
575 such as polychlorinated dibenzo-*p*-dioxins (PCDDs) and polychlorinated dibenzofurans (PCDFs)<sup>21</sup>. This  
576 can be a matter of concern in some countries, such as China<sup>152</sup>. However, when regulation and controls  
577 are implemented, no increased level of pollutants can be measured in the vicinity of cement plants<sup>153–</sup>  
578 <sup>155</sup>. As heavy metals<sup>156</sup> and other hazardous compounds are incorporated in the clinker and cement  
579 kiln dust<sup>60,157</sup>, appropriate control devices and exhaust filters can mitigate heavy metal and hazardous  
580 air emissions<sup>60,157</sup>. Furthermore, the high temperatures and the alkaline conditions in cement plants  
581 allow for the full decomposition of the fuel's organic part<sup>154,158,159</sup>.

582

583 Emissions at End of life. Leaching from SCMs

584 Several industrial wastes can cause leaching of heavy metals when stockpiled. Yet their use as partial  
585 cement replacement can often stabilize them due to the high pH of interstitial pore solution which  
586 precipitates heavy metals complexes<sup>160</sup>. Such benefits have been shown to be less effective in the case  
587 of poorly cured concrete<sup>161</sup>. While currently used industrial wastes as partial replacement of cement  
588 do not appear to have leaching issues in appropriately cured concrete, alternatives such as municipal  
589 solid waste incineration (MSWI) bottom ash and non-ferrous slags are anticipated to have some  
590 chloride and metal leaching issues<sup>162</sup>. However, even in these cases, it is thought that leaching of  
591 undesirable compounds can be mitigated through the use of pre-treatments to remove or convert  
592 potentially harmful compounds<sup>66</sup>. For instance, pre-hydration or carbonation can be used to reduce  
593 metal leaching from MSWI bottom ashes<sup>163,164</sup>.

594

595

596 **Box 2: Water consumption**

597 Water is one of the main constituents in concrete and its use can be as high as cement consumption  
598 by mass<sup>31</sup>. The direct water consumption used in cement products is equivalent to 400 L per capita  
599 each year. However, this water used as a constituent in concrete represents only about 20% of the  
600 total water consumed in its production<sup>19,165</sup>. The remaining water is energy-related or process-related  
601 <sup>19</sup>. Much of the process-related water is consumed during the quarrying, crushing, and washing of the  
602 raw materials used in the production of cement and concrete, e.g., as a dust suppression method<sup>19,165</sup>.  
603 The energy-related water consumption depends on cement kiln type<sup>157</sup> and the energy mixes which  
604 can vary significantly depending on location<sup>166</sup>. On average, less than 50% of water consumption  
605 associated with concrete production is linked to the cement<sup>19</sup> and water management strategies  
606 should thus be implemented all along the supply chain.

607 The cement and concrete sector plays a minor role in water scarcity discussions, contributing less than  
608 5% of total water withdrawal<sup>167</sup> and in most countries less than 1% of total renewable water resources  
609 <sup>19</sup>. However, water is a complex interwoven environmental issue. For example, a transition from river  
610 aggregate to crushed aggregate in order to have sustainable management of mineral resources  
611 induces an increase in water consumption due to the need for washing crushed aggregates.  
612 Conversely, in emerging countries crushed stone are rarely washed which increase dust problems and  
613 health related issues as well as reducing the strength performance of concrete. There is therefore a  
614 water-mineral resources nexus, and development of crushed gravel has to be combined with closed-  
615 loop water treatment.

616 **6 References**

- 617 1. Slaton, A. *Reinforced Concrete and the Modernization of American Building, 1900-1930*. (John  
618 Hopkins University press, 2001).
- 619 2. Krausmann, F., Lauk, C., Haas, W. & Wiedenhofer, D. From resource extraction to outflows of  
620 wastes and emissions: The socioeconomic metabolism of the global economy, 1900–2015.  
621 *Glob. Environ. Chang.* **52**, 131–140 (2018).
- 622 3. Monteiro, P. J. M., Miller, S. A. & Horvath, A. Towards sustainable concrete. *Nat. Mater.* **16**,  
623 698 (2017).
- 624 4. Bajželj, B., Allwood, J. M. & Cullen, J. M. Designing Climate Change Mitigation Plans That Add  
625 Up. *Environ. Sci. Technol.* **47**, 8062–8069 (2013).
- 626 5. Cullen, J. M., Allwood, J. M. & Bambach, M. D. Mapping the Global Flow of Steel: From  
627 Steelmaking to End-Use Goods. *Environ. Sci. Technol.* **46**, 13048–13055 (2012).
- 628 6. Cullen, J. M. & Allwood, J. M. Mapping the Global Flow of Aluminum: From Liquid Aluminum  
629 to End-Use Goods. *Environ. Sci. Technol.* **47**, 3057–3064 (2013).
- 630 7. Nath, A. J., Lal, R. & Das, A. K. Fired Bricks: CO<sub>2</sub> Emission and Food Insecurity. *Glob.*  
631 *Challenges* **2**, 1700115 (2018).
- 632 8. Barcelo, L., Kline, J., Walenta, G. & Gartner, E. Cement and carbon emissions. *Mater. Struct.*  
633 **47**, 1055–1065 (2014).
- 634 9. Waters, C. N. *et al.* The Anthropocene is functionally and stratigraphically distinct from the  
635 Holocene. *Science (80-. )*. **351**, aad2622–aad2622 (2016).
- 636 10. Francis, A. J. *The Cement Industry, 1796–1914: A History*. (David and Charles Ltd, 1977).
- 637 11. Scrivener, K. L., John, V. M. & Gartner, E. M. Eco-efficient cements: Potential economically  
638 viable solutions for a low-CO<sub>2</sub> cement-based materials industry. *Cem. Concr. Res.* **114**, 2–26  
639 (2018).
- 640 12. Swilling, M. *et al.* *The Weight of Cities: Resource requirements of future urbanization*. UN  
641 *Environment - International Resource Panel* (2018).
- 642 13. UN DESA. *World Urbanization Prospects: The 2018 Revision, Highlights*.  
643 <https://population.un.org/wup/Publications/Files/WUP2018-Highlights.pdf> (2019).
- 644 14. Röck, M. *et al.* Embodied GHG emissions of buildings – The hidden challenge for effective  
645 climate change mitigation. *Appl. Energy* **258**, 114107 (2020).
- 646 15. Hoxha, E., Habert, G., Lasvaux, S., Chevalier, J. & Le Roy, R. Influence of construction material  
647 uncertainties on residential building LCA reliability. *J. Clean. Prod.* **144**, 33–47 (2017).
- 648 16. Davis, S. J. *et al.* Net-zero emissions energy systems. *Science (80-. )*. **360**, eaas9793 (2018).
- 649 17. Huntzinger, D. N. & Eatmon, T. D. A life-cycle assessment of Portland cement manufacturing:  
650 comparing the traditional process with alternative technologies. *J. Clean. Prod.* **17**, 668–675  
651 (2009).
- 652 18. Habert, G., Bouzidi, Y., Chen, C. & Jullien, A. Development of a depletion indicator for natural  
653 resources used in concrete. *Resour. Conserv. Recycl.* **54**, 364–376 (2010).
- 654 19. Miller, S. A., Horvath, A. & Monteiro, P. J. M. Impacts of booming concrete production on  
655 water resources worldwide. *Nat. Sustain.* **1**, 69–76 (2018).
- 656 20. Penrose, B. Occupational Exposure to Cement Dust: Changing Opinions of a Respiratory



- 657 Hazard. *Health History* **16**, 25 (2014).
- 658 21. Van den Heede, P. & De Belie, N. Environmental impact and life cycle assessment (LCA) of  
659 traditional and 'green' concretes: Literature review and theoretical calculations. *Cem. Concr.*  
660 *Compos.* **34**, 431–442 (2012).
- 661 22. Watts, J. Concrete: the most destructive material on Earth. *The Guardian* (2019).
- 662 23. Miller, S. A. & Moore, F. C. Climate and health damages from global concrete production. *Nat.*  
663 *Clim. Chang.* (2020) doi:10.1038/s41558-020-0733-0.
- 664 24. Habert, G. *Environmental impact of Portland cement production. Eco-Efficient Concrete*  
665 (2013). doi:10.1533/9780857098993.1.3.
- 666 25. Sogut, M. Z., Oktay, Z. & Hepbasli, A. Energetic and exergetic assessment of a trass mill  
667 process in a cement plant. *Energy Convers. Manag.* **50**, 2316–2323 (2009).
- 668 26. Madloul, N. A., Saidur, R., Hossain, M. S. & Rahim, N. A. A critical review on energy use and  
669 savings in the cement industries. *Renew. Sustain. Energy Rev.* **15**, 2042–2060 (2011).
- 670 27. Shindell, D., Faluvegi, G., Seltzer, K. & Shindell, C. Quantified, localized health benefits of  
671 accelerated carbon dioxide emissions reductions. *Nat. Clim. Chang.* **8**, 291–295 (2018).
- 672 28. CP/RAC. *Manual of pollution prevention in the cement industry.* (2008).
- 673 29. USEPA. *Emission Factor Documentation for AP-42, Section 11.6: Portland Cement*  
674 *Manufacturing.* (1994).
- 675 30. Nkhama, E. *et al.* Effects of Airborne Particulate Matter on Respiratory Health in a Community  
676 near a Cement Factory in Chilanga, Zambia: Results from a Panel Study. *Int. J. Environ. Res.*  
677 *Public Health* **14**, 1351 (2017).
- 678 31. Miller, S. A., Horvath, A. & Monteiro, P. J. M. Readily implementable techniques can cut  
679 annual CO<sub>2</sub> emissions from the production of concrete by over 20%. *Environ. Res. Lett.* **11**, 1–  
680 7 (2016).
- 681 32. Chevallier, R. Illegal Sand Mining in South Africa. *SALIA policy Brief.* **116**, (2014).
- 682 33. Heard, R., Hendrickson, C. & McMichael, F. C. Sustainable development and physical  
683 infrastructure materials. *MRS Bull.* **37**, 389–394 (2012).
- 684 34. van Oers, L. & Guinée, J. The Abiotic Depletion Potential: Background, Updates, and Future.  
685 *Resources* **5**, 16 (2016).
- 686 35. Langer, W. H. Geologic and societal factors affecting the international oceanic transport of  
687 aggregate. *Nonrenewable Resour.* **4**, 303–309 (1995).
- 688 36. Kecojevic, V., Nelson, T. & Schissler, A. An analysis of aggregates production in the United  
689 States: Historical data and issues facing the industry. *Miner. Energy - Raw Mater. Rep.* **19**, 25–  
690 33 (2004).
- 691 37. Torres, A., Brandt, J., Lear, K. & Liu, J. A looming tragedy of the sand commons. *Science (80-. ).*  
692 **357**, 970–971 (2017).
- 693 38. Shaji, J. & Anilkumar, R. Socio-Environmental impact of river sand mining: an example from  
694 Neyyar River, Thiruvananthapuram District of Kerala, India. *J. Humanit. Soc. Sci.* **19**, 01–07  
695 (2014).
- 696 39. Tejpal, M., Jaglan, M. S., Chaudhary, K. & Haryana, B. S. Geo-environmental consequences of  
697 river sand and stone mining: A case study of narnaul block. *Trans. Inst. Indian Geogr.* **36**, 217–

- 698 234 (2014).
- 699 40. Macedo, A. B., de Almeida Mello Freire, D. J. & Akimoto, H. Environmental management in  
700 the Brazilian non-metallic small-scale mining sector. *J. Clean. Prod.* **11**, 197–206 (2003).
- 701 41. Bringezu, S. *et al.* *Assessing global resource use: A systems approach to resource efficiency and*  
702 *pollution reduction.* (2017).
- 703 42. Schuurmans, A. *et al.* LCA of Finer Sand in Concrete (5 pp). *Int. J. Life Cycle Assess.* **10**, 131–  
704 135 (2005).
- 705 43. Ioannidou, D., Nikias, V., Brière, R., Zerbi, S. & Habert, G. Land-cover-based indicator to assess  
706 the accessibility of resources used in the construction sector. *Resour. Conserv. Recycl.* **94**, 80–  
707 91 (2015).
- 708 44. Ioannidou, D., Meylan, G., Sonnemann, G. & Habert, G. Is gravel becoming scarce? Evaluating  
709 the local criticality of construction aggregates. *Resour. Conserv. Recycl.* **126**, 25–33 (2017).
- 710 45. Magnusson, S., Lundberg, K., Svedberg, B. & Knutsson, S. Sustainable management of  
711 excavated soil and rock in urban areas – A literature review. *J. Clean. Prod.* **93**, 18–25 (2015).
- 712 46. Rubli, S. *KAR-Model - Modelling natural, demolition and excavation material flows for the year*  
713 *2018 in Switzerland (in German).* (2020).
- 714 47. Hu, M., Van Der Voet, E. & Huppes, G. Dynamic Material Flow Analysis for Strategic  
715 Construction and Demolition Waste Management in Beijing. *J. Ind. Ecol.* **14**, 440–456 (2010).
- 716 48. Wang, H., Yue, Q., Lu, Z., Schuetz, H. & Bringezu, S. Total Material Requirement of Growing  
717 China: 1995–2008. *Resources* **2**, 270–285 (2013).
- 718 49. Katagiri, K., Boscov, M. E. G., Teixeira, C. E. & Angulo, S. C. Characterization flowchart for  
719 assessing the potential reuse of excavation soils in Sao Paulo city. *J. Clean. Prod.* **240**, 118215  
720 (2019).
- 721 50. Ouellet-Plamondon, C. M. C. M. & Habert, G. Self-Compacted Clay based Concrete (SCCC):  
722 Proof-of-concept. *J. Clean. Prod.* **117**, 160–168 (2016).
- 723 51. Concrete sustainability Council. *CSC-certification for concrete and its supply chain. Annual*  
724 *Report 2017/2018.* <https://www.concretesustainabilitycouncil.com/annual-report-40> (2019).
- 725 52. Miller, S. A., John, V. M., Pacca, S. A. & Horvath, A. Carbon dioxide reduction potential in the  
726 global cement industry by 2050. *Cem. Concr. Res.* **114**, 115–124 (2018).
- 727 53. Josa, A., Aguado, A., Cardim, A. & Byars, E. Comparative analysis of the life cycle impact  
728 assessment of available cement inventories in the EU. *Cem. Concr. Res.* **37**, 781–788 (2007).
- 729 54. Gartner, E. Industrially interesting approaches to “low-CO<sub>2</sub>” cements. *Cem. Concr. Res.* **34**,  
730 1489–1498 (2004).
- 731 55. IEA-CSI, International Energy Agency & IEA-CSI. *Technology Roadmap - Low-Carbon Transition*  
732 *in the Cement Industry.* [www.wbcscement.org](http://www.wbcscement.org). (2018).
- 733 56. Damtoft, J. S., Lukasik, J., Herfort, D., Sorrentino, D. & Gartner, E. M. Sustainable development  
734 and climate change initiatives. *Cem. Concr. Res.* **38**, 115–127 (2008).
- 735 57. Chen, C., Habert, G., Bouzidi, Y. & Jullien, A. Environmental impact of cement production:  
736 detail of the different processes and cement plant variability evaluation. *J. Clean. Prod.* **18**,  
737 478–485 (2010).
- 738 58. Szabo, L., HidALGO, I., CISCAR, J. C., Soria, A. & Russ, P. *Energy consumption and CO<sub>2</sub>*

- 739 *emissions from the world cement industry*. (2003).
- 740 59. CSI-ECRA. *Technology Papers 2017 Development of State of the Art Techniques in Cement*  
741 *Manufacturing: Trying to Look Ahead*. (2017).
- 742 60. Schneider, M. Process technology for efficient and sustainable cement production. *Cem.*  
743 *Concr. Res.* **78**, 14–23 (2015).
- 744 61. Habert, G., Billard, C., Rossi, P., Chen, C. & Roussel, N. Cement production technology  
745 improvement compared to factor 4 objectives. *Cem. Concr. Res.* **40**, 820–826 (2010).
- 746 62. CEMBUREAU. *Cement industry contributes to waste management. key facts*.  
747 <http://www.cembureau.be> (2005).
- 748 63. CEMBUREAU. The Role of Cement in the 2050 Low Carbon Economy. 1–64 (2013).
- 749 64. Cancio Díaz, Y. *et al.* Limestone calcined clay cement as a low-carbon solution to meet  
750 expanding cement demand in emerging economies. *Dev. Eng.* **2**, (2017).
- 751 65. Lothenbach, B., Le Saout, G., Gallucci, E. & Scrivener, K. Influence of limestone on the  
752 hydration of Portland cements. *Cem. Concr. Res.* **38**, 848–860 (2008).
- 753 66. Snellings, R. Assessing, Understanding and Unlocking Supplementary Cementitious Materials.  
754 *RILEM Tech. Lett.* **1**, 50 (2016).
- 755 67. Chen, C., Habert, G., Bouzidi, Y., Jullien, A. & Ventura, A. LCA allocation procedure used as an  
756 incitative method for waste recycling: An application to mineral additions in concrete. *Resour.*  
757 *Conserv. Recycl.* **54**, 1231–1240 (2010).
- 758 68. Alujas, A., Fernández, R., Quintana, R., Scrivener, K. L. & Martirena, F. Pozzolanic reactivity of  
759 low grade kaolinitic clays: Influence of calcination temperature and impact of calcination  
760 products on OPC hydration. *Appl. Clay Sci.* **108**, 94–101 (2015).
- 761 69. Habert, G., Choupay, N., Escadeillas, G., Guillaume, D. & Montel, J. M. Clay content of  
762 argillites: Influence on cement based mortars. *Appl. Clay Sci.* **43**, 322–330 (2009).
- 763 70. Sánchez Berriel, S. *et al.* Assessing the environmental and economic potential of Limestone  
764 Calcined Clay Cement in Cuba. *J. Clean. Prod.* **124**, 361–369 (2015).
- 765 71. Antoni, M., Rossen, J., Martirena, F. & Scrivener, K. Cement substitution by a combination of  
766 metakaolin and limestone. *Cem. Concr. Res.* **42**, 1579–1589 (2012).
- 767 72. Damineli, B. L., Kemeid, F. M., Aguiar, P. S. & John, V. M. Measuring the eco-efficiency of  
768 cement use. *Cem. Concr. Compos.* **32**, 555–562 (2010).
- 769 73. William, S. *et al.* How much cement can we do without? Lessons from cement material flows  
770 in the UK. *Resour. Conserv. Recycl.* **Submitted**, (2018).
- 771 74. Miller, S. A., Monteiro, P. J. M. M., Ostertag, C. P. & Horvath, A. Comparison indices for design  
772 and proportioning of concrete mixtures taking environmental impacts into account. *Cem.*  
773 *Concr. Compos.* **68**, 131–143 (2016).
- 774 75. Cazacliu, B. & Ventura, A. Technical and environmental effects of concrete production: dry  
775 batch versus central mixed plant. *J. Clean. Prod.* **18**, 1320–1327 (2010).
- 776 76. Wassermann, R., Katz, A. & Bentur, A. Minimum cement content requirements: a must or a  
777 myth? *Mater. Struct.* **42**, 973–982 (2009).
- 778 77. Scrivener, K., John, V. & Gartner, E. M. *Eco-efficient cement: potential, economically viable*  
779 *solutions for low CO2 cement based materials industry*. *UN Environment* (2016) doi:978-3-

- 780 940388-48-3.
- 781 78. John, V. M., Quattrone, M., Abrão, P. C. R. A. & Cardoso, F. A. Rethinking cement standards:  
782 Opportunities for a better future. *Cem. Concr. Res.* **124**, 105832 (2019).
- 783 79. Proske, T., Hainer, S., Rezvani, M. & Graubner, C.-A. Eco-friendly concretes with reduced  
784 water and cement contents — Mix design principles and laboratory tests. *Cem. Concr. Res.* **51**,  
785 38–46 (2013).
- 786 80. John, V. M., Damineli, B. L., Quattrone, M. & Pileggi, R. G. Fillers in cementitious materials —  
787 Experience, recent advances and future potential. *Cem. Concr. Res.* **114**, 65–78 (2018).
- 788 81. Costa, E. B. C., Cardoso, F. A. & John, V. M. Influence of high contents of limestone fines on  
789 rheological behaviour and bond strength of cement-based mortars. *Constr. Build. Mater.* **156**,  
790 1114–1126 (2017).
- 791 82. Formoso, C. T., Soibelman, L., De Cesare, C. & Isatto, E. L. Material Waste in Building Industry:  
792 Main Causes and Prevention. *J. Constr. Eng. Manag.* **128**, 316–325 (2002).
- 793 83. Berodier, E., Aron, L., Princeton, J. & Bartolini, I. Can Sustainability of Concrete Construction  
794 Be Improved Through a Better Understanding of Field Practices? Lessons from Haiti. in  
795 *Proceedings of the International Conference of Sustainable Production and Use of Cement and*  
796 *Concrete*. (eds. Martirena-Hernandez, J., Alujas-Díaz, A. & Amador-Hernandez, M.) (RILEM  
797 Bookseries, 2020).
- 798 84. Scrivener, K. L. *et al.* MOOC on Cement Chemistry and Sustainable Cementitious Materials.  
799 *moc* [https://www.mooc-list.com/course/cement-chemistry-and-sustainable-cementitious-](https://www.mooc-list.com/course/cement-chemistry-and-sustainable-cementitious-materials-edx)  
800 [materials-edx](https://www.mooc-list.com/course/cement-chemistry-and-sustainable-cementitious-materials-edx) (2020).
- 801 85. Kourehpaz, P. & Miller, S. A. Eco-efficient design indices for reinforced concrete members.  
802 *Mater. Struct.* **52**, 96 (2019).
- 803 86. Habert, G. *et al.* Reducing environmental impact by increasing the strength of concrete:  
804 quantification of the improvement to concrete bridges. *J. Clean. Prod.* **35**, 250–262 (2012).
- 805 87. Orr, J. J., Darby, A. P., Ibell, T. J., Evernden, M. C. & Otlet, M. Concrete structures using fabric  
806 formwork. *Struct. Eng.* **89**, 20–26 (2011).
- 807 88. De Wolf, C., Pomponi, F. & Moncaster, A. Measuring embodied carbon dioxide equivalent of  
808 buildings: A review and critique of current industry practice. *Energy Build.* **140**, 68–80 (2017).
- 809 89. Shanks, W. *et al.* How much cement can we do without? Lessons from cement material flows  
810 in the UK. *Resour. Conserv. Recycl.* **141**, 441–454 (2019).
- 811 90. Miller, S. A. The role of cement service-life on the efficient use of resources. *Environ. Res. Lett.*  
812 (2019) doi:10.1088/1748-9326/ab639d.
- 813 91. Hajiesmaeili, A., Pittau, F., Denarié, E. & Habert, G. Life Cycle Analysis of Strengthening  
814 Existing RC Structures with R-PE-UHPFRC. *Sustainability* **11**, 6923 (2019).
- 815 92. Habert, G., Denarié, E., Šajna, A. & Rossi, P. Lowering the global warming impact of bridge  
816 rehabilitations by using Ultra High Performance Fibre Reinforced Concretes. *Cem. Concr.*  
817 *Compos.* **38**, 1–11 (2013).
- 818 93. Dubois, A. & Gadde, L. E. The construction industry as a loosely coupled system: Implications  
819 for productivity and innovation. *Constr. Manag. Econ.* **20**, 621–631 (2002).
- 820 94. Dainty, A. R. J. & Brooke, R. J. Towards improved construction waste minimisation: a need for  
821 improved supply chain integration? *Struct. Surv.* **22**, 20–29 (2004).

- 822 95. Seaden, G. & Manseau, A. Public policy and construction innovation. *Build. Res. Inf.* **29**, 182–  
823 196 (2001).
- 824 96. Papadonikolaki, E. & Wamelink, H. Inter- and intra-organizational conditions for supply chain  
825 integration with BIM. *Build. Res. Inf.* **45**, 649–664 (2017).
- 826 97. Shi, C., Qu, B. & Provis, J. L. Recent progress in low-carbon binders. *Cem. Concr. Res.* **122**, 227–  
827 250 (2019).
- 828 98. Juenger, M. C. G., Winnefeld, F., Provis, J. L. & Ideker, J. H. Advances in alternative  
829 cementitious binders. *Cem. Concr. Res.* **41**, 1232–1243 (2011).
- 830 99. Lord, M. *Zero Carbon Industry Plan Rethinking Cement*.  
831 <http://media.bze.org.au/ZCIndustry/bze-report-rethinking-cement-web.pdf> (2017).
- 832 100. Habert, G., D’Espinose De Lacaillerie, J. B. & Roussel, N. An environmental evaluation of  
833 geopolymer based concrete production: Reviewing current research trends. *J. Clean. Prod.* **19**,  
834 1229–1238 (2011).
- 835 101. Miller, S. & Myers, R. J. Environmental impacts of alternative cement binders. *Environ. Sci.*  
836 *Technol.* (2019) doi:10.1021/acs.est.9b05550.
- 837 102. Gartner, E. & Sui, T. Alternative cement clinkers. *Cem. Concr. Res.* **114**, 27–39 (2018).
- 838 103. Provis, J. L. Alkali-activated materials. *Cem. Concr. Res.* **114**, 40–48 (2018).
- 839 104. Ben Haha, M., Winnefeld, F. & Pisch, A. Advances in understanding ye’elinite-rich cements.  
840 *Cem. Concr. Res.* **123**, 105778 (2019).
- 841 105. Gourley, J. T. Geopolymers in Australia. *J. Aust. Ceram. Soc.* **50**, (2014).
- 842 106. Bernal, S. A. Advances in near-neutral salts activation of blast furnace slags. *RILEM Tech. Lett.*  
843 **1**, 39 (2016).
- 844 107. Duxson, P., Provis, J., Lukey, G. & Vandeventer, J. The role of inorganic polymer technology in  
845 the development of ‘green concrete’. *Cem. Concr. Res.* **37**, 1590–1597 (2007).
- 846 108. Bernal, S. A., Rodríguez, E. D., Kirchheim, A. P. & Provis, J. L. Management and valorisation of  
847 wastes through use in producing alkali-activated cement materials. *J. Chem. Technol.*  
848 *Biotechnol.* **91**, 2365–2388 (2016).
- 849 109. Walling, S. A. & Provis, J. L. Magnesia-Based Cements: A Journey of 150 Years, and Cements  
850 for the Future? *Chem. Rev.* **116**, 4170–4204 (2016).
- 851 110. Dewald, U. & Achternbosch, M. Why more sustainable cements failed so far? Disruptive  
852 innovations and their barriers in a basic industry. *Environ. Innov. Soc. Transitions* **19**, 15–30  
853 (2016).
- 854 111. Favier, A., De Wolf, C., Scrivener, K. & Habert, G. *A sustainable future for the European*  
855 *Cement and Concrete Industry: Technology assessment for full decarbonisation of the industry*  
856 *by 2050*. (2018) doi:10.3929/ethz-b-000301843.
- 857 112. Zevenhoven, R. & Kohlmann, J. CO<sub>2</sub> Sequestration by Magnesium Silicate Mineral  
858 Carbonation in Finland. in *Second Nordic Minisymposium on Carbon Dioxide Capture and*  
859 *Storage* 13–18 (2001).
- 860 113. Morrison, J., Jauffret, G., Galvez-Martos, J. L. & Glasser, F. P. Magnesium-based cements for  
861 CO<sub>2</sub> capture and utilisation. *Cem. Concr. Res.* **85**, 183–191 (2016).
- 862 114. Atakan, V., Sahu, S., Quinn, S., Hu, X. & De Cristofaro, N. Why CO<sub>2</sub> matters - Advances in a

- 863 new class of cement. *ZKG Int.* **67**, 60–63 (2014).
- 864 115. Meyer, V., de Cristofaro, N., Bryant, J. & Sahu, S. Solidia Cement an Example of Carbon  
865 Capture and Utilization. *Key Eng. Mater.* **761**, 197–203 (2018).
- 866 116. Lehtinen, M. J. Industrial Minerals and Rocks. in *Mineral Deposits of Finland* 685–710  
867 (Elsevier, 2015). doi:10.1016/B978-0-12-410438-9.00026-1.
- 868 117. Morandeau, A., Thiéry, M. & Dangla, P. Investigation of the carbonation mechanism of CH and  
869 C-S-H in terms of kinetics, microstructure changes and moisture properties. *Cem. Concr. Res.*  
870 **56**, 153–170 (2014).
- 871 118. Stefanoni, M., Angst, U. & Elsener, B. *Corrosion rate of carbon steel in carbonated concrete – A*  
872 *critical review. Cement and Concrete Research* vol. 103 35–48 (Pergamon, 2018).
- 873 119. Bertolini, L., Elsener, B., Pedferri, P., Redaelli, E. & Polder, R. B. *Corrosion of Steel in Concrete:*  
874 *Prevention, Diagnosis, Repair, 2nd Edition.* (Wiley, 2014).
- 875 120. Xi, F. *et al.* Substantial global carbon uptake by cement carbonation. *Nat. Geosci.* **9**, 880–883  
876 (2016).
- 877 121. Thiery, M., Villain, G., Dangla, P. & Platret, G. Investigation of the carbonation front shape on  
878 cementitious materials: Effects of the chemical kinetics. *Cem. Concr. Res.* **37**, 1047–1058  
879 (2007).
- 880 122. Thiery, M., Dangla, P., Belin, P., Habert, G. & Roussel, N. Carbonation kinetics of a bed of  
881 recycled concrete aggregates: A laboratory study on model materials. *Cem. Concr. Res.* **46**,  
882 50–65 (2013).
- 883 123. Andersson, R., Fridh, K., Stripple, H. & Häglund, M. Calculating CO<sub>2</sub> Uptake for Existing  
884 Concrete Structures during and after Service Life. *Environ. Sci. Technol.* **47**, 11625–11633  
885 (2013).
- 886 124. Renforth, P. The negative emission potential of alkaline materials. *Nat. Commun.* **10**, 1401  
887 (2019).
- 888 125. Sanjuán, M. Á., Andrade, C., Mora, P. & Zaragoza, A. Carbon Dioxide Uptake by Mortars and  
889 Concretes Made with Portuguese Cements. *Appl. Sci.* **10**, 646 (2020).
- 890 126. CEN, 2019, PD CEN/TR 17310:2019 ‘Carbonation and CO<sub>2</sub> uptake in concrete’, Brussels. *CEN*  
891 (2019).
- 892 127. Blue Planet. Blue planet, economically sustainable carbon capture. [http://www.blueplanet-](http://www.blueplanet-ltd.com/)  
893 [ltd.com/](http://www.blueplanet-ltd.com/) (2020).
- 894 128. Engelsen, C., Mehus, J., Pade, C. & Sæther, D. *Carbon dioxide uptake in demolished and*  
895 *crushed concrete.* (2005).
- 896 129. Suer, P., Lindqvist, J.-E., Arm, M. & Frogner-Kockum, P. Reproducing ten years of road ageing  
897 — Accelerated carbonation and leaching of EAF steel slag. *Sci. Total Environ.* **407**, 5110–5118  
898 (2009).
- 899 130. Zhan, B. J., Xuan, D. X. & Poon, C. S. Enhancement of recycled aggregate properties by  
900 accelerated CO<sub>2</sub> curing coupled with limewater soaking process. *Cem. Concr. Compos.* **89**,  
901 230–237 (2018).
- 902 131. Stefanoni, M., Angst, U. M. & Elsener, B. Kinetics of electrochemical dissolution of metals in  
903 porous media. *Nat. Mater.* **18**, 942–947 (2019).
- 904 132. Scrivener, K. L., John, V. M. & Gartner, E. M. *Eco-efficient cements: Potential, economically*

- 905 *viable solutions for a low-CO<sub>2</sub>, cement- based materials industry.* (2016).
- 906 133. Soja, W., Maraghechi, H., Georget, F. & Scrivener, K. Changes of microstructure and diffusivity  
907 in blended cement pastes exposed to natural carbonation. *MATEC Web Conf.* **199**, 02009  
908 (2018).
- 909 134. Borges, P. H. R., Costa, J. O., Milestone, N. B., Lynsdale, C. J. & Streatfield, R. E. Carbonation of  
910 CH and C–S–H in composite cement pastes containing high amounts of BFS. *Cem. Concr. Res.*  
911 **40**, 284–292 (2010).
- 912 135. Soja, W. Carbonation of low carbon binders. (EPFL, 2019). doi:10.5075/epfl-thesis-9400.
- 913 136. Roussel, N. Rheological requirements for printable concretes. *Cem. Concr. Res.* **112**, 76–85  
914 (2018).
- 915 137. Perrot, A. *3D Printing of Concrete.* (Wiley, 2019). doi:10.1002/9781119610755.
- 916 138. Voldsund, M. *et al.* Comparison of Technologies for CO<sub>2</sub> Capture from Cement Production—  
917 Part 1: Technical Evaluation. *Energies* **12**, 559 (2019).
- 918 139. Sutter, D., Werner, M., Zappone, A. & Mazzotti, M. Developing CCS into a Realistic Option in a  
919 Country’s Energy Strategy. *Energy Procedia* **37**, 6562–6570 (2013).
- 920 140. Rootzén, J. & Johnsson, F. Managing the costs of CO<sub>2</sub> abatement in the cement industry. *Clim.*  
921 *Policy* **17**, 781–800 (2017).
- 922 141. Havercroft, I., Macrory, R. B. & Stewart, R. B. *Carbon Capture and Storage. Emerging Legal*  
923 *and Regulatory Issues.* (Hart Publishing, 2011).
- 924 142. IPCC. *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of*  
925 *1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the*  
926 *context of strengthening the global response to the threat of climate change,.* (World  
927 Meteorological Organization, 2018).
- 928 143. Van Vuuren, D. P. *et al.* the need for negative emission technologies. *Nat. Clim. Chang.* **8**,  
929 (2018).
- 930 144. von Bahr, B. *et al.* Experiences of environmental performance evaluation in the cement  
931 industry. Data quality of environmental performance indicators as a limiting factor for  
932 Benchmarking and Rating. *J. Clean. Prod.* **11**, 713–725 (2003).
- 933 145. Purnell, P. Material Nature versus Structural Nurture: The Embodied Carbon of Fundamental  
934 Structural Elements. *Environ. Sci. Technol.* **46**, 454–461 (2012).
- 935 146. Cemex. Low carbon concrete: If Co<sub>2</sub> reduction started from the initila planning phase (in  
936 French). <https://www.cemex.fr/les-betons-bas-carbone> (2018).
- 937 147. Orr, J. *et al.* Minimising energy in construction: Practitioners’ views on material efficiency.  
938 *Resour. Conserv. Recycl.* **140**, 125–136 (2019).
- 939 148. Hollberg, A., Lützkendorf, T. & Habert, G. Top-down or bottom-up? – How environmental  
940 benchmarks can support the design process. *Build. Environ.* **153**, 148–157 (2019).
- 941 149. Hall, D. M., Algiers, A. & Levitt, R. E. Identifying the Role of Supply Chain Integration Practices  
942 in the Adoption of Systemic Innovations. *J. Manag. Eng.* **34**, 04018030 (2018).
- 943 150. Slater, S. Olympics Cycling: Marginal Gains Underpin Team GB Dominance. *BBC* (2012).
- 944 151. Durrand, J. W., Batterham, A. M. & Danjoux, G. R. Pre-habilitation (i): aggregation of marginal  
945 gains. *Anaesthesia* **69**, 403–406 (2014).

- 946 152. Zou, L. *et al.* Spatial variation of PCDD/F and PCB emissions and their composition profiles in  
947 stack flue gas from the typical cement plants in China. *Chemosphere* **195**, 491–497 (2018).
- 948 153. Schuhmacher, M., Nadal, M. & Domingo, J. L. Environmental monitoring of PCDD/Fs and  
949 metals in the vicinity of a cement plant after using sewage sludge as a secondary fuel.  
950 *Chemosphere* **74**, 1502–1508 (2009).
- 951 154. Zemba, S. *et al.* Emissions of metals and polychlorinated dibenzo(p)dioxins and furans  
952 (PCDD/Fs) from Portland cement manufacturing plants: Inter-kiln variability and dependence  
953 on fuel-types. *Sci. Total Environ.* **409**, 4198–4205 (2011).
- 954 155. Gupta, R. K., Majumdar, D., Trivedi, J. V. & Bhanarkar, A. D. Particulate matter and elemental  
955 emissions from a cement kiln. *Fuel Process. Technol.* **104**, 343–351 (2012).
- 956 156. Ogunbileje, J. O. *et al.* Lead, mercury, cadmium, chromium, nickel, copper, zinc, calcium, iron,  
957 manganese and chromium (VI) levels in Nigeria and United States of America cement dust.  
958 *Chemosphere* **90**, 2743–2749 (2013).
- 959 157. Marceau, M. L. L., Nisbet, M. A. A. & VanGeem, M. G. G. *Life cycle inventory of Portland  
960 cement manufacture.* (2006).
- 961 158. Conesa, J. A., Gálvez, A., Mateos, F., Martín-Gullón, I. & Font, R. Organic and inorganic  
962 pollutants from cement kiln stack feeding alternative fuels. *J. Hazard. Mater.* **158**, 585–592  
963 (2008).
- 964 159. Lv, D. *et al.* Effects of co-processing sewage sludge in cement kiln on NO<sub>x</sub>, NH<sub>3</sub> and PAHs  
965 emissions. *Chemosphere* **159**, 595–601 (2016).
- 966 160. Li, X. ., Poon, C. ., Sun, H., Lo, I. M. . & Kirk, D. . Heavy metal speciation and leaching behaviors  
967 in cement based solidified/stabilized waste materials. *J. Hazard. Mater.* **82**, 215–230 (2001).
- 968 161. Hillier, S. R., Sangha, C. M., Plunkett, B. A. & Walden, P. J. Long-term leaching of toxic trace  
969 metals from Portland cement concrete. *Cem. Concr. Res.* **29**, 515–521 (1999).
- 970 162. Joseph, A., Snellings, R., Van den Heede, P., Matthys, S. & De Belie, N. The Use of Municipal  
971 Solid Waste Incineration Ash in Various Building Materials: A Belgian Point of View. *Materials  
972 (Basel)*. **11**, 141 (2018).
- 973 163. Van Gerven, T. *et al.* Carbonation of MSWI-bottom ash to decrease heavy metal leaching, in  
974 view of recycling. *Waste Manag.* **25**, 291–300 (2005).
- 975 164. Gartner, E. & Hirao, H. A review of alternative approaches to the reduction of CO<sub>2</sub> emissions  
976 associated with the manufacture of the binder phase in concrete. *Cem. Concr. Res.* **78**, 126–  
977 142 (2015).
- 978 165. Mack-Vergara, Y. L. & John, V. M. Life cycle water inventory in concrete production—A  
979 review. *Resour. Conserv. Recycl.* **122**, 227–250 (2017).
- 980 166. Meldrum, J., Nettles-Anderson, S., Heath, G. & Macknick, J. Life cycle water use for electricity  
981 generation: a review and harmonization of literature estimates. *Environ. Res. Lett.* **8**, 015031  
982 (2013).
- 983 167. Cabernard, L., Pfister, S. & Hellweg, S. A new method for analyzing sustainability performance  
984 of global supply chains and its application to material resources. *Sci. Total Environ.* **684**, 164–  
985 177 (2019).
- 986 168. Häfliger, I.-F. *et al.* Buildings environmental impacts' sensitivity related to LCA modelling  
987 choices of construction materials. *J. Clean. Prod.* **156**, (2017).



- 988 169. Flower, D. J. M. & Sanjayan, J. G. Green house gas emissions due to concrete manufacture.  
989 *Int. J. Life Cycle Assess.* **12**, 282–288 (2007).
- 990 170. KBOB. *Ökobilanzdaten im Baubereich 2009/1:2016*. (2016).
- 991 171. Thiery, M., Villain, G., Dangla, P. & Platret, G. Investigation of the carbonation front shape on  
992 cementitious materials: Effects of the chemical kinetics. *Cem. Concr. Res.* **37**, 1047–1058  
993 (2007).
- 994 172. GNR Project.
- 995 173. NF EN 197-1 Avril 2012.
- 996 174. Passer, A., Deutsch, R. & Scherz, M. Beton-LCA – Wie grün ist grau? in *BAU congress 2018*  
997 250–262 (2018).
- 998 175. Müller, C. Use of cement in concrete according to European standard EN 206-1. *HBRC J.* **8**, 1–7  
999 (2012).
- 1000 176. De Wolf, C. Low carbon pathways for structural design : embodied life cycle impacts of  
1001 building structures. (Massachusetts Institute of Technology, 2017).
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- 1003

1004 **7 Glossary**

1005 **Aggregate:** granular material, such as sand, gravel, crushed stone, or iron blast-furnace slag, used with  
1006 a cementing medium to form hydraulic-cement concrete or mortar. Aggregate may be natural,  
1007 manufactured or recycled. Aggregates make up some 60 -80% of the concrete mix. (ASTM C125 R2008)

1008  
1009 **Binder:** Any material with binding property. It generally consists of cementitious material and water.

1010  
1011 **Biomass:** substance wholly comprised of living or recently living (non-fossil) material. (ASTM E1705)  
1012 —When considered as an energy source, biomass may be further subdivided into: (1) primary  
1013 biomass—rapidly growing plant material that may be used directly or after a conversion process for  
1014 the production of energy, and (2) secondary biomass

1015 —biomass residues remaining after the production of fibre, food, or other products of agriculture, or  
1016 biomass by-products from animal husbandry or food preparation that are modified physically rather  
1017 than chemically. Examples include waste materials from agriculture, forestry industries, and some  
1018 municipal operations (manure, saw dust, sewage, etc.) from which energy may be produced

1019  
1020 **C<sub>3</sub>S, C<sub>2</sub>S, C<sub>3</sub>A and C<sub>4</sub>AF:** clinker mineral phases noted with cement chemical notation. C stands for CaO,  
1021 S for SiO<sub>2</sub>, A Al<sub>2</sub>O<sub>3</sub> and F for Fe<sub>2</sub>O<sub>3</sub>.

1022  
1023 **Cement:** a cement sets and hardens by chemical reaction with water and is capable of doing so under  
1024 water. (ASTM C125 R2015)

1025  
1026 **Cement Kiln Dust (CKD):** CKD are collected during the firing of raw materials during the clinker  
1027 manufacturing process. CKD consists of four major components: unreacted raw feed, partially calcined  
1028 feed and clinker dust, free lime, and enriched salts of alkali sulfates, halides, and other volatile  
1029 compounds.

1030  
1031 **Clinker:** the active part of portland cement . It is a dark grey nodular material made by heating ground  
1032 limestone and clay at a temperature of about 1400 °C - 1500 °C.

1033  
1034 **Concrete:** a composite material that consists essentially of a binding medium within which are  
1035 embedded particles or fragments of aggregate; in hydraulic-cement concrete, the binder is formed  
1036 from a mixture of hydraulic cement and water. (ASTM C125 R2015)

1037  
1038 **Filler:** mineral filler, a finely divided mineral product at least 65 % of which passes the 75-µm sieve.  
1039 (ASTM C1777)

1040  
1041 **Gravel:** coarse aggregate resulting from natural disintegration and abrasion of rock or processing of  
1042 weakly bound conglomerate. (see aggregate ) (ASTM C125 R2016)

1043  
1044 **Mortar cement:** a mixture of finely divided hydraulic cementitious material, fine aggregate, and water  
1045 in either the unhardened or hardened state; hydraulic mortar. (ASTM C219)

1046  
1047 **Plaster:** hydraulic cement, a mixture of hydraulic cement, fine aggregate and water that hardens; used  
1048 for coating surfaces, such as ceilings, walls and partitions. (ASTM C219)

1049  
1050 **Ready Mix Concrete:** concrete manufactured and delivered to a purchaser in a fresh state. (ASTM C94)

1051  
1052 **Sand:** fine aggregate resulting from natural disintegration and abrasion of rock or processing of  
1053 completely friable sandstone. (ASTM C125 R2018)

1054

1055 **Supplementary cementitious materials (SCM):** an inorganic material that contributes to the  
1056 properties of a cementitious mixture through hydraulic or pozzolanic activity, or both. Some examples  
1057 of supplementary cementitious materials are fly ash, silica fume, slag cement, rice husk ash, and  
1058 natural pozzolans. In practice, these materials are used in combination with portland cement. (ASTM  
1059 C125 R2015).  
1060

1061 **Figures and tables caption**

1062 **Figure 1: Examples of cement and concrete contribution to the global warming potential.** For  
1063 European building stock, the contribution of building materials is reduced for existing buildings as their  
1064 low energy performance induce large contribution of energy for heating. New buildings have much  
1065 lower emissions during their operation and contribution of embodied emission is higher (Values are  
1066 average value from 230 buildings mainly from Europe (75%) and Asia (25%)<sup>14</sup>). At the building level,  
1067 the embodied emissions from a typical multifamily masonry building come mainly from reinforced  
1068 concrete followed by contribution of windows (Values are average of 35 buildings from France and  
1069 Switzerland built between 2010 and 2015<sup>15,168</sup>). For the production of one cubic meter of concrete the  
1070 main CO<sub>2</sub> emissions come from cement production followed by transport of raw materials (Values are  
1071 the average of main concrete type made with 25% SCMs in Australia<sup>169</sup> and Switzerland<sup>170</sup>). Finally,  
1072 considering current clinker production efficiency and the replacement of 30% SCM in the final cement,  
1073 main emissions are due to decarbonation of limestone and burning fuels, both processes involved in  
1074 clinker production (Values are average French values<sup>57,61,67</sup>).

1075

1076 **Figure 2: Cement value chain.** From raw material extraction until the demolition of the building,  
1077 numerous stakeholder are involved, but very seldom integrated (adapted from<sup>24,111</sup>).

1078

1079 **Figure 3: Carbonation profile through concrete.** Measures and model adapted from<sup>120,171</sup>. Carbon  
1080 uptake range adapted from<sup>122,135</sup>.

1081

1082 **Table 1: Available technologies along the cement and concrete value chain, their improvement**  
1083 **potentials and the stakeholder that should be encourage to take action. (data from<sup>55 172 173 61 174,175</sup>**  
1084 **<sup>89,147,176</sup>)**

1085

1086

1087 **Table 2: Stakeholder description**

1088

1089

1090