SCMs: environmental and qualitative benefits

Concrete is the most widely used construction material in the world and ~10bnta of concrete is produced. With cement accounting for 15 per cent by weight, it stands to reason that the cement industry has a part to play in reducing CO_2 emissions. A reduction in the clinker-to-cement ratio through the use of blended cements incorporating supplementary cementitious materials (SCMs) can reduce CO_2 and other greenhouse gas emissions.

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The construction industry is a large contributor of CO_2 emissions globally, in part due to cement's high carbon footprint, accounting for approximately nine per cent of anthropogenic CO_2 gases, along with sulphur dioxide and nitrogen oxides. According to the US Environmental Protection Agency,[1] the cement sector is the third-largest industrial cause of pollution, contributing 2.5 per cent more CO_2 than aviation and 12 per cent more than the agriculture.These high quantities of carbon emissions are generated for the most part in clinker production.[2]

Figure 1 illustrates emissions along the cement industry supply chain, indicating that 90 per cent come from clinker production, of which 50 per cent are process emissions and 40 per cent are thermal emissions due to heating the materials at high temperatures in the kiln. The remaining 10 per cent of emissions are accounted for by quarrying, preparation of materials, cooling, grinding, mixing and transportation.[3]

CO_2 emissions from global cement manufacturing have increased dramatically in the last 30 years. Figure 2 below shows China as having the highest CO_2 emissions (~827Mt), as the country manufactures over 50 per cent of global production, generating 20 times more emissions than the USA in 2019.[4]

Emissions generated by cement production can be reduced by many means, from using alternative fuels to improving efficiency. However, reducing the clinker-to-cement ratio by using supplementary cementitious materials (SCMs) can be the most expeditious and economical method in the short-term.

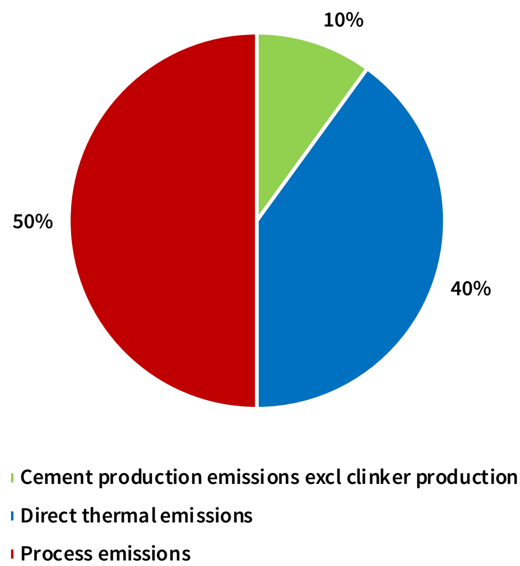
About SCMs

SCMs are a cementitious addition to concrete that partially substitutes Portland cement. Examples of materials used as SCMs are blastfurnace slag, fly ash, silica fume and natural pozzolans.[5]

There are benefits to the use of SCMs, such as improving durability, diminishing alkali-silica reaction and enhancing other concrete properties for infrastructure applications.

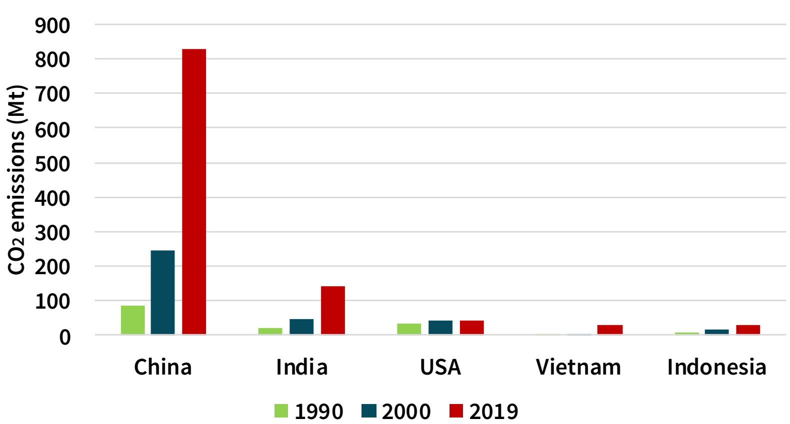
SCMs originate in nature as pozzolanic minerals or are produced industrially, more commonly as by-products of industrial processes. The SCMs that are more readily available are: coal combustion residuals, ground granulated

Figure 1: emissions along the cement supply chain



Adapted from Preston, F and Lehne, J [3]

Figure 2: global cement manufacturing CO_2 emissions by country, 1990-2019



Adapted from Statista [4]

blastfurnace slag (GGBS), silica fume and natural pozzolans.[6]

Coal combustion residual

A by-product resulting from coal combustion in power plants is fly ash – small particles chemically composed of SiO_2, CaO, Fe_2O_3, and Al_2O_3.[7] Fly ash is an excellent component for blended cements or concrete due to its potential for pozzolanic activity, but fly ash is usually limited to 15-25 per cent of replacement levels for cement in concrete.[7]

High-volume fly ash (HVFA) concrete contains 40 per cent fly ash by mass of total SCMs, developing high concrete strength and high resistance to alkali-silica reaction when replacing cement by 40-70 per cent fly ash.[7] It greatly supports reducing emissions and overcoming crucial problems focussed on sustainable construction.[6]

Even though the use of fly ash results in many benefits (such as improving concrete performance, workability, strength and durability), the wide variation in the fineness, the chemical composition, and the mineralogy of the fly ash when developing an ideal composition of concrete with HVFA remains quite complex.[8]

GGBS

This material is a by-product of the manufacture of iron in the blast furnace. GGBS is appropriate for ready-mix concrete, site-batched concrete and precast product manufacturing.[9]

GGBS has resulted in high-strength and -performance concrete when used as cement replacement, having more compressive and flexural strength than regular concrete when replacing cement by 40 per cent.[9] However, due to considerable variations of physical properties of GGBS from the different sources and regions, the effect that it has on the concrete also changes substantially.[9]

Silica fume

This material was part of the end-of-life products from industrial processes, but now it is used for "ultra-high performance concrete".[6] Silica fume is a fine powder formed by very small particles of SiO_2, 100 times smaller than cement particles, providing relatively high pozzolanic activity and creating a "net effect" resulting in better adhesion among the paste, the aggregate, and the cement.[6]

As noted by Nicoara et al (2020)[6], the use of silica fume as a supplementary cementitious material positively affects the concrete, increasing mechanical properties due to efficient filling, improving the concrete durability in the long term, and concrete strength in both the long and short terms. In addition, silica fume improves concrete density (reducing porosity), and reduces bleeding and segregation, resulting in superior performance concrete.

Furthermore, silica fume improves the mechanical strength of concrete and other physical and chemical properties such as decreasing permeability and increasing protection against corrosion for reinforcing steel bars, while lowering emissions to the environment.[6]

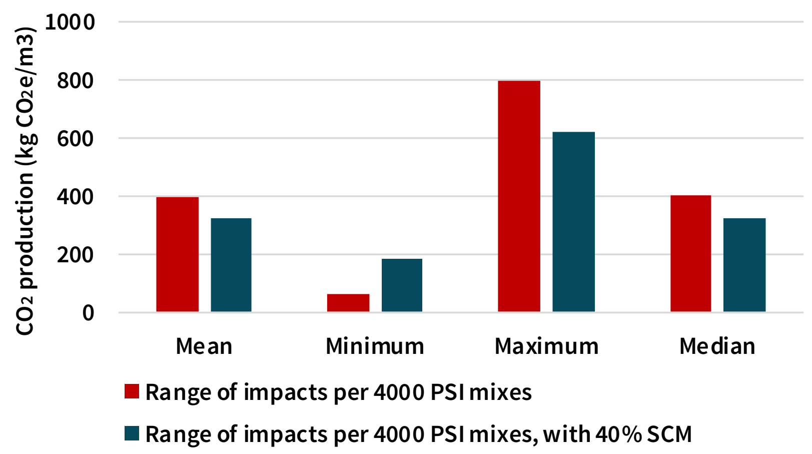
Raw and calcined pozzolans

Natural pozzolans (volcanic ash) are siliceous materials with cementitious value that can be used as a cement substitute in concrete or to make pozzolanic cements, found in natural mineral and volcanic deposits.[10] Common synthetic pozzolans are calcined clay, shale and metakaolin, while less common ones include rice husk ash.[10]

Natural pozzolans are packed together over time into vast deposits of tuffs and other rhyolitic minerals.[11] Volcanic ash possessing pozzolanic behaviour without the calcination process are denoted as true natural pozzolans.[10]

Calcined pozzolans are materials derived from clays and shales. After applying considerable heat, these materials transform into pozzolans. After the calcination process, the material is ground into a fine powder to be used as an SCM.[10]

Figure 3: range of impacts per 4000PSI mixes, with 0 per cent vs 40 per cent SCM



Adapted from Climate Earth Inc [14]

Environmental benefits

The use of materials such as fly ash and GGBS as SCMs instead of being placed in landfills results in environmental benefits due to a reduced demand for fuel and limestone.[12] Additional environmental benefits are derived from these materials because they are by-products from other industries. Having the required pozzolanic and cementitious properties makes them ideal for reducing the clinker demand while keeping "similar compressive strength at certain replacement levels".[13]

Climate Earth Inc[14] compared a regular mix of cement against the use of SCMs, as shown in Figure 3. This figure contrasts the impact for 4000PSI concrete mixes using a standard Portland cement mix (0 per cent of SCM) against using 40 per cent of SCM substitution, indicating an average production of 398kg of CO_2 equivalent/m^3 concrete versus 325kg of CO_2 equivalent/m^3, respectively. As a result, the report shows that a 40 per cent SCM substitution decreases CO_2 released to the environment by 20 per cent.

Hossain et al[12] determined that concrete made with SCMs using the mix designs listed in Table 1 resulted in a reduction of 20 per cent (MD-2), 38 per cent (MD-3), and 24 per cent (MD-4) of greenhouse gas (GHG) emissions compared to using only ordinary Portland cement in the concrete mix (MD-1).

The study also demonstrated a reduction in energy consumption when using SCMs in the concrete mix designs, 15 per cent (MD-2), 29 per cent (MD-3) and 20 per cent (MD-4), respectively. The findings from Hossain et al (2018) determined that the use of SCMs in the concrete mix

Table 1: mix design (MD) of different concrete types used in the study

Materials (kg/m³)	MD-1	MD-2	MD-3	MD-4
Ordinary Portland cement (kg/m³)	445	333	238	315
Granulated blastfurnace slag (kg/m³)	0	142	237	0
Fly ash (kg/m³)	0	0	0	105
Silica fume (kg/m³)	0	0	25	0
Coarse aggregates (kg/m³)	905	935	935	1020
Fine aggregates (kg/m³)	745	680	605	718
Water (kg/m³)	208	221	221	172
Admixture (kg/m³)	1.69	1.81	2.1	1.8
Total weight (kg)	2304.69	2312.81	2263.10	2331.80
28-day compressive strength (MPa)	58.70	60.80	66.00	53.30

Adapted from Hossain, M, Poon, C, Dong, Y, and Xuan, D [12]

"Fly ash, GGBS and silica fume have shifted from industrial waste to a by-product status, improving concrete quality and having advantages from an environmental perspective."

reduced the carbon emissions released to the environment.

Fly ash, GGBS and silica fume have shifted from industrial waste to a by-product status, improving concrete quality and having advantages from an environmental perspective.[15] The primary treatment of 1kg of the SCMs stated before means fewer emissions to the air (SO_x, NO_x, and dust) when compared with 1kg of ordinary Portland cement, establishing that the partial replacement of cement is highly beneficial for the environment. [15]

Samad et al [9] presented a study by the UK Concrete Industry Alliance tabulated by Higgins [16] that exemplified the environmental benefits of using GGBS and fly ash as a replacement of cement in concrete, shown in Table 2.

Table 2 shows a reduction of 40 per cent CO_2 emissions when replacing 50 per cent of Portland cement with GGBS and an insignificant impact in mineral extraction (eight per cent). Also, there is a 17 per cent CO_2 emissions reduction when replacing 30 per cent of Portland cement with fly ash. Additionally, Higgins [16] concluded that in 2005 the UK saved 2.5Mt of CO_2 emissions, 2MMW hours of energy, 4Mt of mineral extraction, and potentially 2.5Mt of material sent to landfills thanks to the use of fly ash and GGBS in concrete.

Nevertheless, Miller [13] concluded that, depending on the SCM type and the changes in transportation, "high levels of SCM replacement do not consistently result in lower GHG emissions for concrete production per unit strength". For instance, Miller determined that transportation (distance and mode) can counterbalance the advantages of using SCMs for reducing GHG emissions. For this reason, every project should be considered based on global parameters, including logistics.

Qualitative benefits in concrete

Sanytsky et al [17] analysed the implementation of blended cements as an optimal solution to low carbon emissions in the cement industry and evaluated the impact that SCMs, such as GGBS and superfine zeolites (SFZ), and limestone additives had on their physical and mechanical properties, evaluating compressive strength as shown in Figure 4.

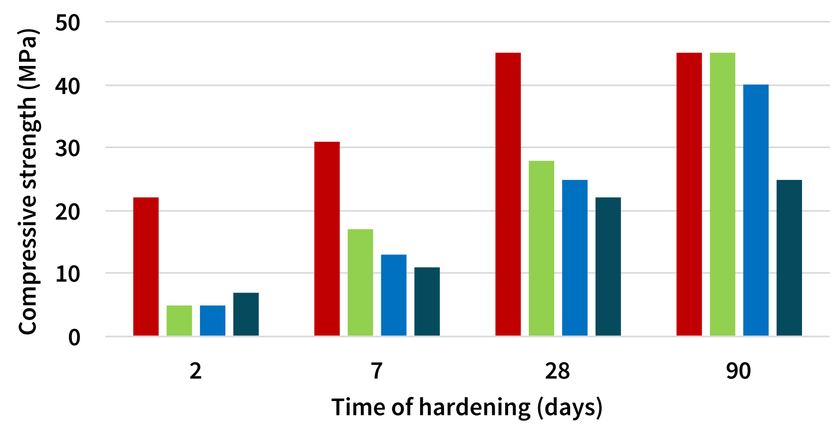
The results of compressive strength tests carried out by Sanytsky et al [17] demonstrates that even though a high volume of SCMs in the blended cement mix decreases its compressive strength at an early stage, this will end up increasing over time, resulting in values close to a 100 per cent of ordinary Portland cement's compressive strength by 90 days (see Figure 4).

Table 2: calculated environmental impacts for 1t of concrete

Impact	100% Portland cement	50% GGBS + 50% Portland cement	30% fly ash + 70% Portland cement
Greenhouse gas – CO_2 (kg)	142 (100%)	85.4 (60%)	118 (83%)
Primary energy use (MJ)	1070 (100%)	760 (71%)	925 (86%)

Note: the environmental impacts are per tonne production of a C30 concrete. Adapted from Higgins, D [16]

Figure 4: test results of blended cements' compressive strengths



Adapted from Sanytsky, M, Kropyvnytska, T, Ivashchyshyn, H and Rykhlitska, O [17]

Table 3: workability, sitting times of metakaolin (MK) concretes

Concrete mixes	Compressive strength (MPa)
Ordinary Portland cement	87.0
MK 5% replacement	91.5
MK 10% replacement	104.0
MK 15% replacement	103.5

Adapted from Ahmed, R, Jaafar, MS, Bareq, M, Hejazi, F and Rashid, RS [18]

Furthermore, Hossain et al [12] determined in the results of their study based on different concrete mix designs, shown in Table 2, a lower acidification impact from the mixes MD-2, MD-3 and MD-4 compared to MD-1 (OPC cement) of 14, 30 and 18 per cent, respectively.

The use of metakaolin (MK) as a supplementary cementitious material is also beneficial for concrete quality. Ahmed et al[18] stated that using MK as a partial replacement of cement will increase by 20 per cent the compressive strength of concrete. The finest compressive strength is reached by 10 per cent substitution, as shown in Table 3, improving the mechanical properties of concrete along with its quality and resistance.

Diedrick[19] indicated that even though the concrete has many advantages, like workability and finishability in its plastic state, the SCMs improve its hardened properties.

Slag cement and fly ash in the early stages will lower concrete strength but after the 28-day and beyond will substantially increase its long-term strength. Furthermore, SCMs will reduce permeability to chloride at later stages, improving the durability of concrete structures.[19]

Diedrick [19] also indicated that SCMs help concrete resist an alkali-silica reaction (ASR), sulphate attack and thermal stress. ASR is responsible for expanding and cracking concrete and SCMs can prevent this. Usually blends of silica fume and slag cement or silica fume and fly ash prevent ASR expansion. Sulphates also can cause an expansion in ordinary Portland cement when reacting with alumina. However, SCMs prevent these sulphate attacks due to small compounds that react with these while keeping out sulphate-bearing waters. The application of slag cement and fly ash in balanced mixes can also prevent cracking and deterioration of structural integrity due to thermal stress by reducing high temperatures and heat generation rates.

"The cement industry has a significant impact on the environment. In the search to reduce this impact, SCMs can play a major role in reducing the environmental impacts generated by the production of concrete. More than 20 per cent of potential greenhouse gases can be reduced by using SCMs instead of ordinary Portland cement."

Conclusions

The cement industry has a significant impact on the environment. In the search to reduce this impact, SCMs can play a major role in reducing the environmental impacts generated by the production of concrete. More than 20 per cent of potential greenhouse gases can be reduced by using SCMs instead of ordinary Portland cement.

In addition to reducing greenhouse emissions, SCMs provide qualitative benefits to concrete. As a result, SCMs provide strength improvement to concrete, increase concrete life, and resist alkali-silica reactions, sulphate attacks and thermal stress. ■

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