Global and National CO_2 Uptake by Cement Carbonation from 1928 to 2024

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Abstract. The hydration products of cement materials can absorb atmospheric CO_2, and this carbonation process provides an important decarbonization pathway for the cement industry. Global carbon sequestration by cement materials has been reported, but carbon uptake in different countries remains unquantified. Here, we quantify the national cement carbon uptake from 1928 to 2023 based on 58517 activity level data from 163 cement-producing countries and regions worldwide and 6186 carbonation parameters from detailed data records of 42 countries, and project their trend to 2024. The global CO_2 uptake by cement materials increases from 7.74 Mt yr^{-1} (95% confidence interval, CI: 5.84-9.85 Mt CO_2 yr^{-1}) in 1928 to 0.84 Gt yr^{-1} (95% CI: 0.71-1.00 Gt yr^{-1}) in 2023, and projected to rise to 0.86 Gt yr^{-1} (95% CI: 0.73-1.02 CO_2 yr^{-1}) in 2024. The accumulated CO_2 uptake from 1928 to 2023 is 21.26 Gt CO_2 (95% CI: 17.93-25.17 Gt CO_2), which offsets about 46% of the cement process emissions (46.06 Gt CO_2) in past 96 years. Simultaneously, the dominance in cement carbon uptake has shifted from the USA, Japan and some European countries to emerging economies such as China and India, which account for 38.0% and 9.1% of total CO_2 uptake, respectively, in the last decade (2014-2023). By analysing the long time-series carbon emissions and uptake of the 42 countries with detailed data, we find they contributed 82.1% of global cement CO_2 uptake from 1928 to 2023**,** including 21 peaked countries and 21 non-peaked countries in cement emissions**.** The annual carbon offset level (the ratio of uptake to process emissions in a given year) shows a remarkable decrease due to the temporal lag of cement carbon uptake. This is significant for countries with higher cement imports, for example, the cement industry in Australia and Japan have achieved net-zero when considering the cement carbonation sink. This study provides an accurate bottom-up quantification of cement carbonation sinks at national and global levels. All the data described in this study are accessible at https://doi.org/10.5281/zenodo.14583866 (Wu et al., 2024)

1 Introduction

The global cement industry is the third largest source of difficult-to-eliminate CO_2 emissions, after load-following electricity and iron and steel (Davis et al., 2018; Shah et al., 2022), accounting for up to 8% of anthropogenic CO_2 emissions (Cheng et al., 2023; Farfan et al., 2019). Cement production CO_2 emissions arise from fossil energy inputs (about 40%) and calcination of carbonates (mostly $CaCO_3$) induced process emissions (about 60%). As the largest source of carbonate decomposition emissions, global cement production process emissions in 2023 were about 1.6 Gt CO_2 (Andrew, 2019). Conversely, cement products such as concrete and mortar are important CO_2 sinks because of their capacity to react with environmental CO_2 (Snæbjörnsdóttir et al., 2020). The carbonation mechanism of cement is mainly attributed to alkaline hydration products (Xue et al., 2021), such as calcium hydroxide [$\mathrm{Ca(OH)_2}$], calcium silicate [$\mathrm{(CaO)_3} \cdot x\mathrm{SiO_2}$] and calcium aluminate [$\mathrm{CaO} \cdot x\mathrm{Al_2O_3}$], as described by the following equations (Goyal and Sharma, 2020):

$$Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O \tag{1}$$

$$(CaO)_3 \cdot xSiO_2 + CO_2 \rightarrow xSiO_2 + CaCO_3 \tag{2}$$

$$CaO \cdot xAl_2O_3 + xH_2O + CO_2 \rightarrow xAl(OH)_3 + CaCO_3 \tag{3}$$

A substantial fraction of process CO_2 emissions from cement production is reabsorbed on a time scale of 100 years through natural carbonation of cement materials, the net cement emissions (industrial process of cement production minus the estimated annual CO_2 sequestration from carbonation of cement materials) have been reduced by 43% compared to cumulative process emissions without absorption from 1930 to 2013 (Xi et al., 2016).

The cement carbon uptake is helpful to achieve the cement net-zero ambitions for the cement industry (CEMBUREAU, 2024). Although studies have demonstrated the significant reduction of CO_2 emissions through the use of industrial by-products as substitutes for raw materials (Coffetti et al., 2022; Kurtis, 2015) and the use of alternative fuels to meet the energy needs (de Lorena Diniz Chaves et al., 2021), carbon sequestration of cement carbonation plays an essential role to reach the net-zero emissions goal for the cement industry. Therefore, there is an urgent need to scientifically quantify the contribution of cement carbonation in the decarbonization efforts of the cement industry. Currently, the Roadmap to Carbon Neutrality, published by the Portland Cement Association of the United States (PCA, 2024), highlights approximately 10% of the CO_2 generated during the manufacture of cement and concrete can ultimately be absorbed over the life of a concrete structure (not including cement mortar), and it underscores the significance of recognizing and validating cement carbonation. The European Cement Association (CEMBUREAU, 2024) has proposed a cement net-zero ambition by 2050, with mineral carbonation contributing about 6.4% (74kg CO_2/t reduction) to achieving this emissions goals. The report indicated explicitly that the CO_2 absorption facilitated by concrete structures and infrastructure should be incorporated into national greenhouse gas inventories. In addition, the estimates of cement carbon uptake are used by the Global Carbon Budget (Friedlingstein et al., 2023) as an important part of anthropogenic carbon sink for modelling of the annual global carbon cycle. Therefore, it is imperative that these uptake estimates are as accurate as possible.

However, due to the lack of detailed activity data and accurate carbonation parameters for various countries, there is still a gap in national-scale accounting of cement carbon uptake. Cement consumption, influenced by international trade, provides the activity level data for estimating carbon sequestration (Ambec et al., 2024). In previous accounting, cement production was used as a proxy for consumption (Xi et al., 2016). However, while that is sufficient at the global level – since production and consumption are almost equal globally – to achieve more accurate results at the country level is imperative to collect more accurate activity data on cement consumption with improved spatial resolution. To establish a national cement carbon sink database, it is essential to refine cement carbonation parameters at the national level, including cement type, exposure conditions, and building lifespan, which directly impact cement carbonation properties.

Many studies have made great contributions to a better understanding of cement carbon emissions. Andrew (2019) provided a long time series global cement carbon emissions database by calibrating carbon emissions from cement production processes across various countries. Cheng et al. (2023) offered bottom-up quantifications of emissions in developing countries. Some studies accounted for cement emissions and proposed reduction strategies, particularly in major emitters like China (Doh Dinga and Wen, 2022; Liu et al., 2021) and India (Krishna Priya et al., 2024). Nonetheless, the corresponding carbon sequestration accounting for cement with the same accuracy has not yet been established. It is therefore imperative to enhance the spatial resolution of the cement carbon uptake database to understand the specifics of cement carbon sinks and their contributions to emissions reductions across different countries.

This study is the fourth update of the Global Cement Carbon Uptake Database, providing a detailed bottom-up quantification and revealing a shift in the main countries contributing to global cement CO_2 uptake. Key updates compared to previous versions (Xi et al., 2016; Guo et al., 2021; Huang et al., 2023) are: (1) Global cement carbon uptake is now calculated as the sum of 163 countries and regions, offering a more comprehensive view than the previous coarse-scale partition summation. (2) To reduce accounting uncertainty, we have shifted from using cement clinker production to apparent consumption as the activity level data for national cement carbon sequestration accounting. (3) We have updated national-level cement carbonation parameters to improve accounting accuracy, including factors such as cement utilization type, concrete strength class, and concrete exposure time. (4) The database has been updated to include time series from 1928 to 2023, with projected cement carbon uptake for 2024 aligning with the latest Global Carbon Budget. (5) This update also highlights the cement carbon sequestration characteristics at national-level and their carbon offset levels to process emissions.

2 Methods and data sources

2.1 Data sources and treatment

In this study, national cement clinker production data and emission factors were used to calculate carbon emissions from cement production processes. The cement clinker production data for 163 countries and regions were obtained from two sources: (1) Direct cement clinker production data submitted to the United Nations Framework Convention on Climate Change (UNFCCC) by 43 countries. (2) Estimated cement clinker production data were derived by multiplying clinker-to-cement ratio (the ratio of cement clinker production to cement production) with cement production. Cement production data for 163 countries and regions from 1928 to 2022 were accessed from the United States Geological Survey (USGS: Cement statistics and information, 2025). For the year 2023, the cement production data was updated from the CCF2Up database website (https://ccf2up.com/). For countries lacking updated data for 2023 and all countries in 2024, projections were made based on historical data (see Sect. 2.3 for forecasting methods). The cement-to-clinker ratio data for China and India aligned with our prior research (Xi et al., 2016; Guo et al., 2021; Huang et al., 2023). For other countries, the ratios are estimated using the methods outlined by Andrew (2020), with taking 95% clinker-to-cement ratio for the years before 1970 and employing linear interpolation to estimate the ratio for the period after 1970, based on an assumption of steady increases in clinker substitution over time. Country-specific cement emission factors are obtained from the UNFCCC for 43 countries. For those not listed in the database, the default value of 0.507 kg CO_2/t clinker provided by the Intergovernmental Panel on Climate Change (IPCC, 2006) was used.

To provide a more accurate national-level database of carbon uptake in cement, the following data updates have been made in this study based on previous work (Huang et al., 2023), incorporating the following modifications: (1) Cement consumption for 163 countries and regions. Cement consumption in different countries was adjusted using import and export data (accessed on UN Comtrade Database at https://comtradeplus.un.org/) for cement clinker based on the cement production data collected and estimated for each country. (2) The proportion of cement used for concrete and mortar in 42 countries, which is the share of concrete and mortar in total cement consumption respectively. Statistics on the types of cement utilized in European countries were sourced from the European Ready-Mixed Concrete Industry (ERMCO, 2019). Data for South Africa (Muigai et al., 2013), India (Kumar and Kaushik, 2003) and Thailand were collected from the literatures. For China and the USA, the data remains consistent with previous work. (3) Concrete strength is a comprehensive parameter for assessing its quality and the carbonization rate generally decreases with increasing concrete strength class (Pade and Guimaraes, 2007), so we collected data on concrete strength classes for 42 countries. For European countries, concrete strength class data were derived and updated from European Ready Mixed Concrete Organization statistics (ERMCO, 2019). For other countries like Brazil, Egypt, South Africa, Saudi Arabia, India, Malaysia, Thailand, and the UAE, the concrete categories were estimated based on building types from China Economic Information Center Data (CEIC, 2024). (4) Building lifespan determines the exposure time of concrete during the service stage, which is crucial for setting up the concrete lifecycle in the accounting model. Therefore, we collected data on the distribution of building lifespans for 42 countries. Building lifespan data were primarily referenced from statistical and survey data(Xi et al., 2016), for countries with limited statistical data, such as Vietnam and India, engineering design and model data were used (Bhyan et al., 2023，Ji et al., 2021). Altogether, there are 58517 activity level data for 163 cement-producing countries and regions worldwide, and 6186 carbonation parameters for 42 countries were updated and enriched in the calculate model of global cement carbon uptake. The detailed activity level data and carbonation parameters are in Supplementary table 1-2 (available from https://doi.org/10.5281/zenodo.14583866, Wu et al., 2024).

2.2 Estimating for cement process CO_2 emissions

The methodology recommended by IPCC is widely used for estimating CO_2 emissions from industrial processes. In this study, we used Tier 2 method to estimate country-specific emissions (Eq. 4):

$$E_{process,i} = P_{cement,i} \times f_{clinker,i} \times EF_{CO_2,i} \tag{4}$$

where $E_{process,i}$ represents process CO_2 emissions from cement industry in country i; $P_{cement,i}$ refers to weight (mass) of cement produced, $f_{clinker,i}$ is clinker-to-cement ratio, $EF_{CO_2,i}$ is the country-specific emission factor for clinker.

2.3 Estimating for cement CO_2 uptake

We employ national geographic boundary as the accounting boundary for cement carbon uptake, aligning with the accounting methods for carbon emissions from cement production. The accounting model for cement CO_2 uptake (Table 1) in this study adheres to the model constructed in our prior research, which can be summarized as follows:

$$C = W \times f \times \gamma \times F \times M \tag{5}$$

$$W = P_{clinker} - Ex + Im \tag{6}$$

$$F = d/D \tag{7}$$

$$d = k \times \sqrt{t} \tag{8}$$

$$k = \beta_{csec} \times \beta_{ad} \times \beta_{CO_2} \times \beta_{cc} \tag{9}$$

Where *C* is the carbon uptake by cement materials, *W* is the clinker consumption, which is adjusted by clinker production ($P_{clinker}$) with its exports (*Ex*) and imports (*Im*) (Eq. 6). *f* is the proportion of CaO in cement clinker, γ is the fraction of CaO converted to $CaCO_3$ of cement material. *F* is annual carbonation proportion, which is the percentage of carbonation depth (*d*) in accounting year compared to the theoretical maximum carbonation depth (*D*) (Eq. 7). Based on Fick's diffusion law (Eq. 8, You et al., 2022), the carbonation depth of cement is the product of the carbonation rate (*k*) and the square root of time. The carbonation rate in the model is calculated by considering the impact of exposure conditions (β_{csec}), cement additives (β_{ad}), CO_2 concentration (β_{CO_2}) and coating and cover (β_{cc}) (Eq. 9). M is the molar mass ratio of CO_2 to CaO (44/56≈0.786). Considering the carbon uptake mechanism of cement in different life cycles, cement carbon uptake has been categorized into four types: (1) concrete use, (2) mortar use, (3) construction-loss, and (4) cement kiln dust (CKD) landfills. For concrete, the carbon uptake takes into whole life cycle of concrete service, demolition, and secondary-use (including both disposal in a landfill and recycling). For cement mortar, there are comprise three kinds of use: rendering and plastering mortar, maintenance and repairing mortar, and masonry mortar. Concrete and mortar loss are both carbon sinks for construction-loss cement. The carbon uptake of CKD occurs during landfill disposal. Table 1 lists the carbon sequestration accounting equations for different cement materials.

Table 1: Accounting Model for Cement CO_2 uptake

Cement type	Disposal method or Life stages	Accounting formula
(1) Concrete	Service	$C_{li} = W_{li} \times F_{li} \times f_{clinker} \times f_{CaO} \times \gamma \times \frac{M_{CO_2}}{M_{CaO}}$ $F_{li} = d_{li}/D_{li}$ $d_{li} = 2k_{li} \times \sqrt{t_l}$
	Demolition	$C_d = W_{di} \times F_{di} \times f_{CaO} \times \gamma \times \frac{M_{CO_2}}{M_{CaO}}$ $F_{di} = \begin{cases} 100\% - \frac{\int_a^b \frac{\pi}{6}(D - D_{di})^3}{\int_a^b \frac{\pi}{6} D^3} \times 100\%, & (a > D_{di}) \\ 100\% - \frac{\int_{D_{di}}^b \frac{\pi}{6}(D - D_{di})^3}{\int_a^b \frac{\pi}{6} D^3} \times 100\%, & (a \leq D_{di} < b) \\ 100\%, & (b \leq D_{di}) \end{cases}$ $D_{di} = 2d_{di} = 2k_{di} \times \sqrt{t_d}$
	Secondary-use	$C_s = W_{si} \times F_{si} \times f_{CaO} \times \gamma \times \frac{M_{CO_2}}{M_{CaO}}$ $F_{si} = \begin{cases} 100\% - \frac{\int_a^b \frac{\pi}{6}(D - D_{si})^3}{\int_a^b \frac{\pi}{6} D^3} \times 100\% - F_{di}, & (a > D_{si}) \\ 100\% - \frac{\int_{D_{si}}^b \frac{\pi}{6}(D - D_{si})^3}{\int_a^b \frac{\pi}{6} D^3} \times 100\% - F_{di}, & (a \leq D_{si} < b) \\ 100\% - F_{di}, & (b \leq D_{si}) \end{cases}$ $D_{si} = 2d_{ti} = 2k_{si} \times \sqrt{t_{si} + t_{di} + \Delta t_i}$
(2) Mortar	Rendering and plastering mortar	$C_{rpt} = \sum_0^t W_m \times r_{rp} \times f_{rpt} \times f_{clinker} \times f_{CaO} \times \gamma_1 \times \frac{M_{CO_2}}{M_{CaO}}$

		$f_{rpt}=\frac{d_{rpt}-d_{rp(t-1)}}{d_{Trp}}\times 100\%$ $d_{rp}=K_m\times\sqrt{t}$
	Maintenance and repairing mortar	$C_{rmt}=\sum_{0}^{t}W_m\times r_{rr}\times f_{rmt}\times f_{clinker}\times f_{CaO}\times \gamma_1\times\frac{M_{CO_2}}{M_{CaO}}$ $f_{rmt}=\frac{d_{rmt}-d_{rm(t-1)}}{d_{Tmp}}\times 100\%$ $d_{rm}=K_m\times\sqrt{t}$
	Masonry mortar	$C_{rmat}=\sum_{i=0}^{2}W_m\times r_{rm}\times r_{rmat-i}\times f_{rmat-i}\times f_{clinker}\times f_{CaO}\times \gamma_1\times\frac{M_{CO_2}}{M_{CaO}}$ $f_{rmat-0}=\begin{cases}\frac{2\left(d_{rmat-0}-d_{ram(t-1)-0}\right)}{d_w}\times 100\%, & (t\le t_r)\\ 100\%-2d_{rmat-0-sl}/d_w\times 100\%, & (t_r\le t\le t_{sl})\end{cases}$ $d_{rmat-0}=2K_m\times\sqrt{t}$ $f_{rmat-1}=\begin{cases}\frac{d_{rmat-1}-d_{ram(t-1)-1}}{d_w}\times 100\%, & (t_r\le t\le t_{sl})\\ 100\%-\frac{(2d_{rmat-1-sl}-2d_{Trp})}{d_w}\times 100\%, & (t=t_{sl}+1)\end{cases}$ $d_{rmat-1}=\begin{cases}K_m\times\sqrt{t}, & (t\le t_r)\\ K_m\times\sqrt{t}+(K_m\times\sqrt{t}-d_{Trp}), & (t_r\le t\le t_{sl})\end{cases}$ $f_{rmat-2}=\begin{cases}0, & (t\le t_r)\\ \frac{d_{rmat-2}-d_{ram(t-1)-2}}{d_w}\times 100\%, & (t_r\le t\le t_{sl})\\ 100\%-\frac{(d_{rmat-2-sl}-2d_{Trp})}{d_w}\times 100\%, & (t=t_{sl}+1)\end{cases}$ $d_{rmat-2}=\begin{cases}0, & (t\le t_r)\\ 2(K_m\times\sqrt{t}-d_{Trp}), & (t>t_r)\end{cases}$
(3) Construction-loss	Waste concrete	$C_{wastecon}=(\sum_{1}^{n}W_{ci}\times f_{con}\times r_{con})\times f_{clinker}\times f_{CaO}\times\gamma\times\frac{M_{CO_2}}{M_{CaO}}$
	Waste mortar	$C_{wastemor}=(\sum_{1}^{n}W_{mi}\times f_{mor}\times r_{mor})\times f_{clinker}\times f_{CaO}\times\gamma_1\times\frac{M_{CO_2}}{M_{CaO}}$
(4) Cement kiln dust (CKD)	Landfill	$C_{CKD}=W_{clinker}\times r_{CKD}\times r_{landfill}\times f_{CaO}\times\gamma_2\times\frac{M_{CO_2}}{M_{CaO}}$

Annotation: (1) Concrete: $\boldsymbol{W_{li}}$, $\boldsymbol{W_{di}}$, $\boldsymbol{W_{si}}$: cement consumption for i grade strength concrete in the construction services, demolition and secondary use phases; $\boldsymbol{F_{li}}$, $\boldsymbol{F_{di}}$, $\boldsymbol{F_{si}}$: carbonization ratio for i grade strength concrete in the construction services, demolition and secondary use phases; $\boldsymbol{D}$: particle size of concrete debris in the demolition phase of construction; $\boldsymbol{D_{li}}$: Wall thickness during concrete service; $\boldsymbol{D_{di}}$, $\boldsymbol{D_{si}}$: maximum particle size of i grade strength concrete for complete carbonization in the construction demolition and secondary use phases; **a, b**: maximum and minimum particle size of waste concrete debris; $\boldsymbol{d_{li}}$, $\boldsymbol{d_{di}}$, $\boldsymbol{d_{si}}$**:** carbonation depth of i grade strength concrete in the construction services, demolition and secondary use phases; $\boldsymbol{k_{li}}$, $\boldsymbol{k_{di}}$, $\boldsymbol{k_{si}}$: carbonation rate of i grade strength concrete in the construction services, demolition and secondary use phases; $\boldsymbol{t_l}$, $\boldsymbol{t_d}$, $\boldsymbol{t_{si}}$, $\boldsymbol{t_{di}}$, $\boldsymbol{\Delta t_i}$: use time of i grade strength concrete buildings, exposure time during the demolition phase, secondary use time of burial, and carbonation lag time for burial; $\boldsymbol{f_{CaO}}$: proportion of CaO in cement clinker; $\boldsymbol{\gamma}$: fraction of CaO converted to $CaCO_3$ of concrete; $\boldsymbol{M_{CO_2}}$, $\boldsymbol{M_{CaO}}$: molar mass of CO_2 and CaO.

(2) Mortar: $\boldsymbol{W_m}$: cement consumption for mortar; $\boldsymbol{r_{rp}}$, $\boldsymbol{r_{rr}}$, $\boldsymbol{r_{rm}}$: proportion of mortar used for rendering and plastering, maintenance and repairing, masonry; $\boldsymbol{r_{rmat-i}}$: proportion of masonry mortar that does not have plaster (i=0), plaster on one side (i=1) and plaster on both sides (i=2); $\boldsymbol{f_{rpt}}$, $\boldsymbol{f_{rmt}}$, $\boldsymbol{f_{rmat-i}}$: carbonization ratio in year t for three mortars; $\boldsymbol{\gamma_1}$: fraction of CaO converted to $CaCO_3$ of mortar; $\boldsymbol{d_{rpt}}$, $\boldsymbol{d_{rmt}}$, $\boldsymbol{d_{rmat-i}}$: carbonation depth of different types mortar in year t; $\boldsymbol{d_{rp(t-1)}}$, $\boldsymbol{d_{rm(t-1)}}$, $\boldsymbol{d_{rma(t-1)-i}}$: carbonation depth of different types mortar in year t-1; $\boldsymbol{d_{Trp}}$, $\boldsymbol{d_{Tmp}}$, $\boldsymbol{d_w}$: thickness of mortar used for rendering and plastering, maintenance and repairing, masonry; $\boldsymbol{K_m}$: carbonation rate of mortar; $\boldsymbol{t}$: mortar exposure time; $\boldsymbol{t_r}$: time required for complete carbonation of plaster mortar at thickness.

(3) Construction-loss: $\boldsymbol{W_{ci}}$, $\boldsymbol{W_{mi}}$: cement consumption for i grade strength concrete and mortar; $\boldsymbol{f_{con}}$, $\boldsymbol{f_{mor}}$: loss rate of concrete and mortar during the construction phase; $\boldsymbol{r_{con}}$, $\boldsymbol{r_{mor}}$: carbonation ratio of lost concrete and lost mortar during the construction phase.

(4) Cement kiln dust (CKD): $\boldsymbol{W_{clinker}}$: cement clinker production; $\boldsymbol{r_{CKD}}$: production rate of CKD; $\boldsymbol{r_{landfill}}$: proportion of cement kiln ash used for landfill disposal; $\boldsymbol{\gamma_2}$: fraction of CaO converted to $CaCO_3$ of CKD

2.4 Projection of 2024 cement uptake

We provide a projection of cement process carbon emissions and uptake for 163 countries and regions in the year 2024. We use the autoregressive integrated moving average model, or ARIMA (p, d, q), a time-series analysis method commonly used for yield forecasting. This regression-based model forecasts values by regressing the variable's past values using various lag lengths, along with the current and past values of the error term (Cox and Vladescu, 2023). Based on extensive long-term cement production data spanning from 1928 to 2023 for 163 countries and regions, we use the ARIMA model to forecast cement production for the year 2024 and cross-validated the model (see SI data 1 in Supplementary table 1 for details). Our forecasts are further validated by industry economic reports from major cement-producing nations. For example, 2023 Cement Industry Economic Operation Report published by the China Cement Association (CCA, 2024) considers upstream raw materials prices and the downstream real estate market, projecting a 2-3% decline in cement production by 2024. This prediction aligns with our model's 2.1% decline. Similarly, for United States, the USGS provided monthly data on cement production, showing a 4% year-over-year decline in the first half of 2024 that is consistent with our model's trend prediction. The 2024 cement clinker consumption data is adjusted based on import and export data in recent years and used to forecast cement carbon uptake in 2024.

2.5 Uncertainty analysis

We employed the Monte Carlo method suggested by the IPCC to simulate the cement carbon emissions and uptake 10,000 times to assess the uncertainty in cement production process emissions and carbon sequestration in cement materials. The results of uncertainty accounting are in Supplementary table 4 (available from https://doi.org/10.5281/zenodo.14583866, Wu et al., 2024). We identified 24 variables that contribute to uncertainty in cement carbon uptake. This count is two less than previous version due to the revised cement clinker production and clinker-to-cement ratio. The 24 variables include: 3 variables related to cement clinker, namely CaO content, MgO content, and the proportion of CaO converted to $CaCO_3$; 10 variables for concrete, including strength class, proportion of cement for concrete, carbonation rate, building lifespan, particle size distribution, demolition exposure time, and correction factor; 6 variables for mortar, including proportion of cement for mortar, type of utilization, mortar thickness, and carbonation rate; 2 variables for building loss, including utilization ratio and carbonation period; and 3 variables for CKD, including production rate, landfill ratio, and CaO content.

Compared to our previous study, this study reduces the uncertainty of global cement carbon uptake estimations. The improvements in accuracy are reflected in three aspects: (1) The activity level data used in this study is based on the annual apparent consumption of cement clinker in each country, which is adjusted by the international trade (import/export) of clinker. This updated national level activity data reduces the uncertainty range of [-30.0%, 30.6%] in previous estimations, which arose due to the approximated substitution of cement production data for consumption data. (2) The clinker-to-cement ratio used in the previous versions were based on IPCC guideline-recommended values (86%, with an uncertainty range of [75%, 97%]), while in this study we have refined the clinker-to-cement ratio by conducting annual fitting for each country, which further reduces the uncertainty. (3) We updated the country-specific cement carbonation parameters, including cement utilization proportion in concrete and mortar, concrete strength classes, and building lifespan, which greatly improved the accuracy compared to using global clustered parameters for carbon uptake calculation in our previous reports.

3 Results and Discussions

3.1 Global cement carbon emissions and uptake

Global cement process emissions and carbon uptake. Global cement process emissions have increased from 34.58 Mt CO_2 yr^{-1} in 1928 to 1.58 Gt CO_2 yr^{-1} in 2023, with an average annual growth rate of 4.1%, and a cumulative emission of 46.07 Gt CO_2 over past 96 years (Fig. 1a). The increase of global cement process emissions is closely linked to the significant expansion in cement clinker production, which increased 45-fold since 1928, with an average annual growth rate of 4.1%. Correspondingly, global carbon uptake by cement has increased from 7.74 Mt CO_2 yr^{-1} (95% CI: 5.84-9.85 Mt CO_2 yr^{-1}) in 1928 to 0.84 Gt CO_2 yr^{-1} (95% CI: 0.71-10.03 Gt CO_2 yr^{-1}) in 2023. Notably, 79.2% of cement carbon sinks occurred since

1990. The total amount of CO_2 uptake by cement over the years is estimated to be 21.26 Gt CO_2 (95% CI: 17.93-25.17 Gt CO_2), indicating that cement has reabsorbed approximately 46.1% of the process emissions from its production process. Unsurprisingly, the carbon offset level (uptake-to-emissions ratio, Fig. 1b) show a clearly overall increasing trend over the past nearly 100 years. This trend is primarily due to the time-lag of cement carbonation, unlike the transient carbon process emissions from cement, the gradual accumulation of historical carbon sequestration results in a steady increase in carbon offset level. This effect becomes particularly evident during periods of declining cement production. For instance, during the Second World War in 1944, when global cement clinker production declined by 28.2%, the carbon offset level rose to 45.0%, an increase of 15.8% compared to the previous year. Conversely, periods of rapid growth in cement process carbon emissions, such as the period between 2000 and 2007, which saw an average annual growth rate of 7.0% in cement clinker production due to accelerated urbanization and industrialization, witnessed a decline in the carbon offset level at an average annual rate of 0.7%. This trend is primarily due to the time-lag of cement carbonation, such that much of the carbonation occurs in the years following the cement's production. The results show that global cement carbon uptake in 2022 was 0.82 Gt CO_2 (95% CI: 0.69-0.98 Gt CO_2 yr^{-1}), a decrease of 1.1% from 2021. It mainly attributable to the decline in both global cement production and apparent cement consumption in 2022, which decrease by 5.6% and 6.2% from 2021, respectively. In particular, as the largest cement producer, China's cement production and apparent consumption decreased by 11.1%. In 2023, global cement carbon uptake shows a 2.8% increase from 2022, in which the global cement production declined by 1.4%, but the apparent consumption of cement clinker increased by 2.0%. This suggests a strong correlation between cement carbon uptake and cement consumption. A modest recovery in global cement consumption is anticipated for 2024, primarily driven by rapidly growing markets in South-East Asia and Africa (Cheng et al., 2023). This recovery is expected to correspond with a continuation of growth in the global cement carbon uptake, which is forecasted to reach 0.86 Gt CO_2 (95% CI: 0.73-10.23 Gt CO_2 yr^{-1}), marking an increase of 2.0% from the 2023 levels.

Global carbon uptake by different cement products. The carbon uptake of all cement material types increased steadily (Fig. 1c). Mortar is the most important cement product for CO_2 sequestration, with an average annual uptake of 0.37 Gt yr^{-1} (95% CI: 0.32-0.42 Gt CO_2 yr^{-1}) in last decade (2014-2023), accounting for 48.0% of the total (Fig. 1d). This is largely explained by mortar's much higher surface-to-volume ratio than concrete's. Since 1928, mortar's CO_2 uptake has increased from 4.64 Mt yr^{-1} (95% CI: 3.55-5.95 Mt yr^{-1}) to 0.39 Gt yr^{-1} (95% CI: 0.34-0.44 Gt yr^{-1}), with an average annual growth rate of 4.7%. The CO_2 uptake by concrete also played a significant role, with an average annual uptake of 0.32 Gt yr^{-1} in the last decade, contributing to 41.5% of the total. Its uptake increased from 1.43 Mt yr^{-1} (95% CI: 1.11-1.67 Mt yr^{-1}) in 1928 to 0.37 Gt yr^{-1} (95% CI: 0.31-0.45 Gt yr^{-1}) in 2023, with an average annual growth rate of 6.0%. CKD and construction-loss cement absorbed respectively 0.05 and 0.025 Gt CO_2 yr^{-1} in last decade, contributing 7.2% and 3.3% of the total carbon uptake, with average annual growth rates of 4.1% and 4.4% from 1928 to 2023. We project that mortar, concrete, CKD, and construction-loss in 2024 will absorb 0.40, 0.38, 0.06, and 0.027 Gt CO_2 yr^{-1}, respectively. From the share of carbon sinks by different cement materials, we find that the share of concrete carbon uptake has similar trend with carbon offset level (Fig. 1b). Notably, concrete is the main material contributing to the time-lag effect of cement carbon sinks due to its exposure conditions and larger fragment particle size which reduce the carbonation occurring within the first year. The significant carbon sequestration of cement materials makes them one of important carbon sinks in the global carbon cycle. It is necessary to strengthen the carbonation management of cement materials during the waste disposal and recycling stage. For example, many studies have explored the mechanisms and properties of accelerated carbonation in cement materials, such as waste concrete (Mo and Panesar, 2013), and CKD (Pu et al., 2023). Certainly, carbon capture is widely regarded as the only viable solution for significantly reducing CO_2 emissions from cement production to meet the 2050 mitigation targets (Schneider, 2019), but further research is required to assess the economic costs and potential risks associated with their implementation.

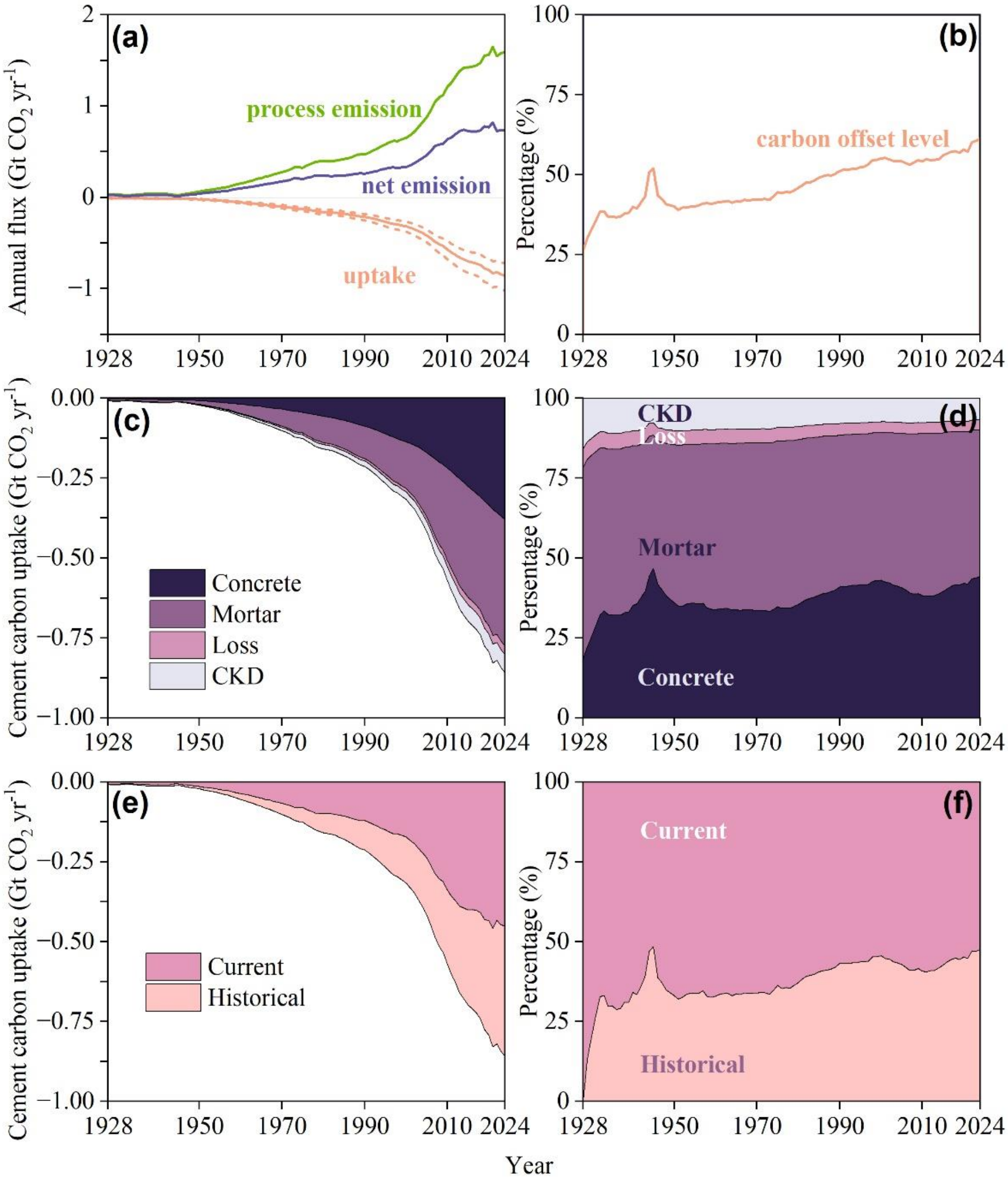


Figure 1: Global cement CO_2 uptake. (a) global annual process CO_2 emissions and uptake by cement. (b) carbon offset level (share of CO_2 uptake to emissions). (c) global annual CO_2 uptake by four cement material. (d) share of CO_2 uptake by four cement materials. (e) global cement annual CO_2 uptake in current and historical year. (f) share of CO_2 uptake by current and historical. The detailed results data are in Supplementary table 3 (available from https://doi.org/10.5281/zenodo.14583866, Wu et al., 2024)

Time-lag effect of cement carbon uptake. The cement carbon uptake in both current-year and historical-year shows increasing trend (Fig. 1e). The current-year carbon uptake, which represents the absorption of CO_2 by cement produced in the current year, has increased from 9.08 Mt CO_2 yr^{-1} in 1928 to 0.54 Gt CO_2 yr^{-1} in 2023, with an average annual growth rate of 4.4%. While the historical-year uptake refers to carbon uptake due to incomplete carbonization of cement materials consumed in the historical years and continues to carbonize in the current year, increasing to 0.42 Gt yr^{-1} in 2023. Our projections indicate that in 2024, the current-year uptake and historical-year uptake will reach 0.45 and 0.41 Gt CO_2 yr^{-1}, respectively, with increases of 0.9% and 3.2% compared to 2023. Current-year uptake is the main contributor to the global cement uptake, with an average annual share of 62.7% during the 1928-2023 period (Fig. 1f). It is noteworthy that the trend in the share of historical-year uptake aligns with the carbon offset level. In 1944, when cement consumption decreased, the share of historical-year carbon uptake rose to 47.0%. Conversely, during the period from 2000 to 2007, when cement consumption increased rapidly, the share of historical-year carbon uptake decreased at an average rate of 1.5%. This pattern suggests that the carbon offset level of cement carbonation sinks will increase as cement production and consumption decline in the future. Specifically, the annual carbonation rate of cementitious materials shows a steady decline (Figure 2). Mortar and CKD, with their faster carbonation rates, are the primary cement materials contributing to current-year uptake. While concrete is the main material result in the time-lag effect of cement carbon sinks (Figure 2), it is because natural carbonation of concrete cannot be completed in one year (Pan et al., 2016) and the rate of carbonation gradually slows down (Qiu, 2020). For example, the carbon uptake of cement consumed in 1990 was 121 Mt, while the sequestration from the same cement has decreased to only 2.0 Mt in 2023.

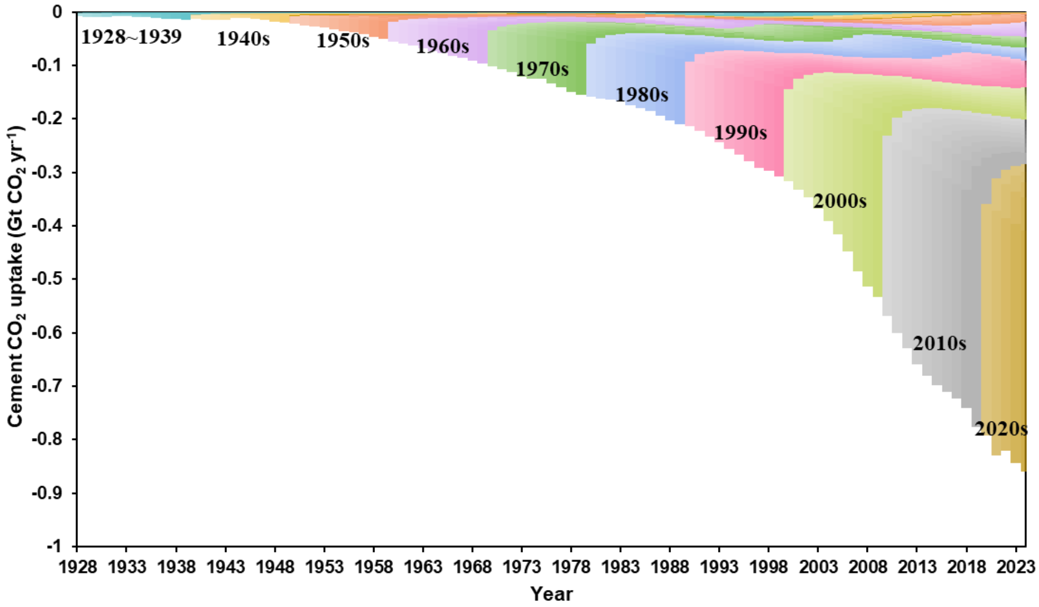


Figure 2: Time-lag effect on carbon uptake by cement from 1928 to 2024. Different colours represent changes in carbon sequestration over time for different years of consumption of cement.

3.2 Spatial distribution of cement carbon uptake

In this study, we gathered carbonation parameters from 42 countries to enrich the cement uptake accounting model. Figure 3 shows the share of cement CO_2 uptake by 42 countries and the rest of world (ROW) during 1928-2023. The cumulative carbon uptake by cement in these 42 countries is 16.60 Gt CO_2 in the past 96 years, accounting for 78.1% of the global total. Their contributions peaked in 1928 (95.6%) and were minimal in 1984 (72.9%). It is evident that cement CO_2 uptake by China and other emerging economies, including South Africa, Indonesia, Vietnam, Korea, India, Turkey, Mexico, and Brazil, have gradually replaced the leading roles played by the USA, Japan, and countries in European like the United Kingdom, Spain, Italy, Germany, France, Canada, and Belgium after 1982. Specifically, the USA was the largest contributor to cement carbon uptake with an average contribution of 23.6% between 1928 and 1991. From 1928 to 1966, Germany and the UK were major contributors alongside the USA, with contribution of 8.7% and 6.9% respectively. From 1967 to 1982, Japan became the second-largest contributor with an average contribution of 8.2%. After that, between1983 and 1991, China replaced Japan with an average contribution of 11.9%. Since 1992, China has been the country with largest amount of cement carbonation sinks, reaching a maximum contribution of 43.5% in 2020. Additionally, since 2008, India has been the second-largest contributor, replacing Japan's position during 1992-2006. In 2023, the cement carbon uptake in China and India were 0.33 Gt CO_2 yr^{-1} (38.0% of global, CI: 0.25 - 0.41 Gt yr^{-1}) and 0.07 Gt CO_2 yr^{-1} (9.1%, 0.06-0.09 Gt yr^{-1}), respectively.

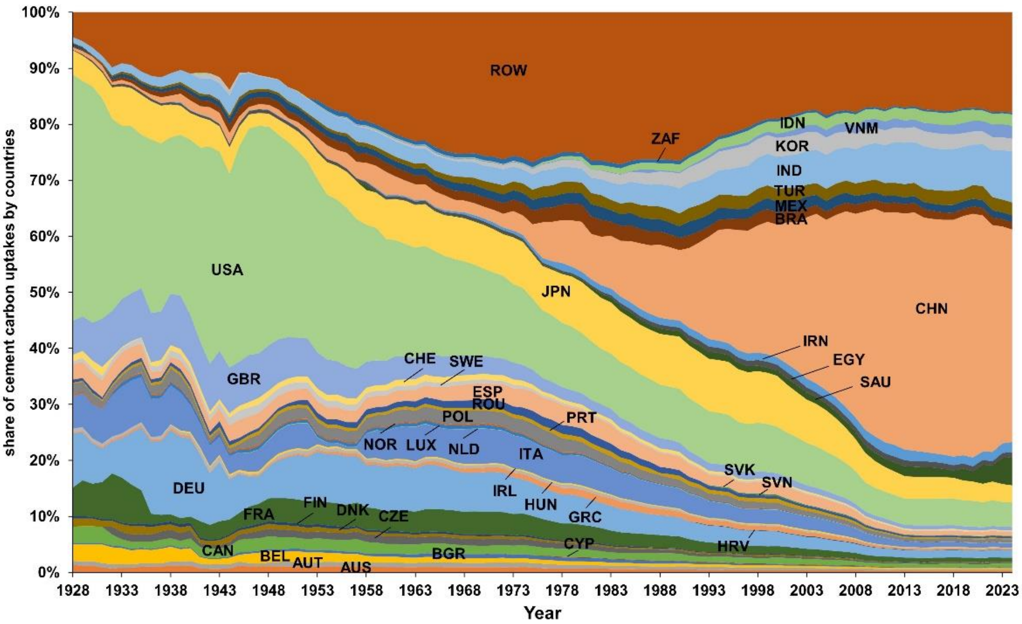


Figure 3: Share of cement carbon uptake from 1928 to 2023 by 42 countries and rest of world (ROW). The full names corresponding to the country abbreviations are as follows: AUS (Australia), AUT (Austria), BEL (Belgium), BGR (Bulgaria), CAN (Canada), HRV (Croatia), CYP (Cyprus), CZE (Czechia), DNK (Denmark), FIN (Finland), FRA (France), DEU (Germany), GRC (Greece), HUN (Hungary),

IRL (Ireland), ITA (Italy), LUX (Luxembourg), NLD (Netherlands), NOR (Norway), POL (Poland), PRT (Portugal), ROU (Romania), SVK (Slovakia), SVN (Slovenia), ESP (Spain), SWE (Sweden), CHE (Switzerland), GBR (United Kingdom), USA (USA), MEX (Mexico), BRA (Brazil), EGY (Egypt), TUR (Turkey), IRN (Iran), SAU (Saudi Arabia), IND (India), CHN (China), KOR (Korea, Republic of), JPN (Japan), VNM (Vietnam), IDN (Indonesia), ZAF (South Africa).

Based on the clinker production data for 163 countries and regions worldwide and the carbonation parameters for 42 countries, we estimated and projected the carbon uptake across these 163 entities. From the spatial distribution of the cement CO_2 uptake in 2024 (Fig. 4), We find that the dominant countries of carbon uptake by cement are still distributed in Asia, particularly due to the region's high demand for infrastructure development. China leads the global charge with 326.84 Mt CO_2 (44.0% of the total), followed by India and Saudi Arabia with 78.25 and 43.76 Mt CO_2, respectively. Japan and South Korea are ranked 7th and 10th with 25.99 and 19.33 Mt CO_2 sequestration, respectively. Southeast Asian countries like Vietnam, Indonesia, Thailand, Philippines, and Laos also contribute significantly, sequestering 19.91, 17.54, 9.34, 7.68 and 5.68 Mt CO_2, respectively. For America, the main countries for CO_2 uptake are in USA, Brazil, Mexico, and Canada, with 37.91, 11.03, 10.53 and 5.20 Mt respectively, which ranked 4th, 12th, 14th, and 28th in the world. In Africa, cement carbon uptake is concentrated in Egypt, Nigeria, Algeria and South Africa, which sequester 7.49, 4.30, 4.17 and 2.53 Mt CO_2, respectively. In Europe, key countries for CO_2 sequestration via cement are Germany, Italy, France, Spain, United Kingdom, and Poland, with amounts of 11.00, 6.82, 6.35, 5.97, 5.11 and 4.46 Mt, respectively.

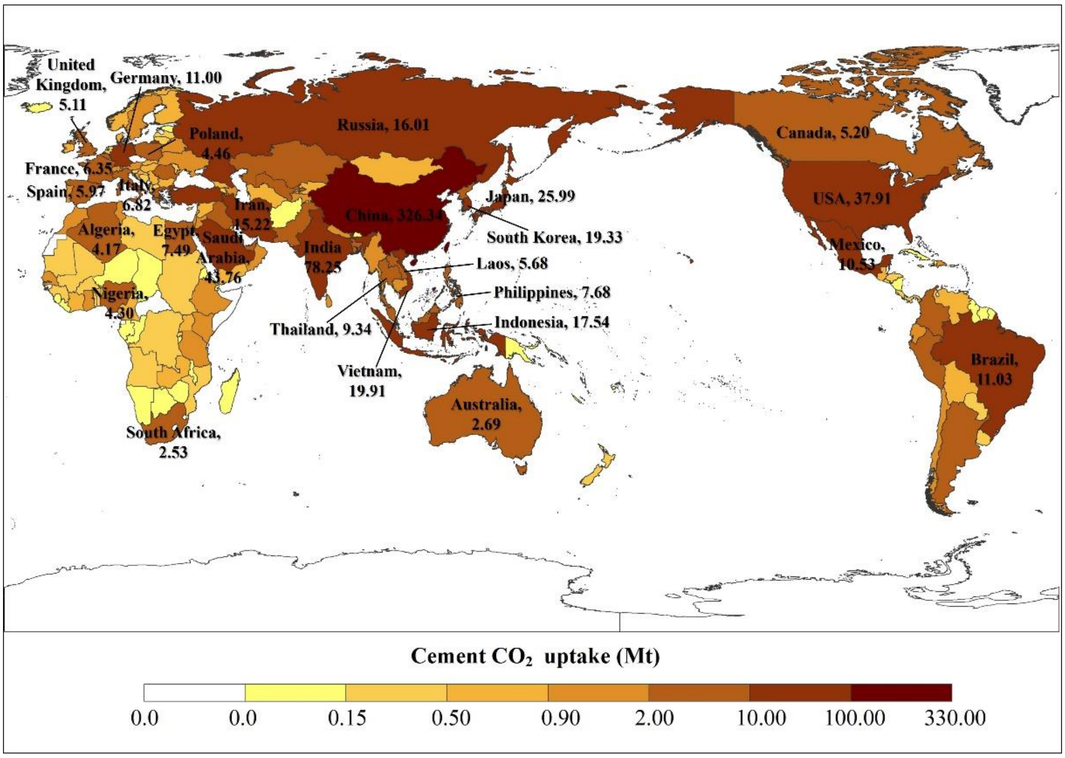


Figure 4: Spatial distributions of cement CO_2 uptake in 2024. (The map is copyrighted by the Institute of Geographic Sciences and Resources of the Chinese Academy of Sciences, with no modifications to the base map)

3.3 National cement carbon emissions and uptake

In this study, we enriched the national cement process carbon emissions and uptake database. We categorized the countries into two sets according to the trends of their cement process carbon emissions curves (Table 2). Group 1 comprises 21 countries where the process carbon emissions have shown a peaking trend during 1928-2024. These countries can be further divided into 2 categories based on their net emissions trends: 9 countries with a neutral trend (category a1) and another 12 countries that have peaked but do not exhibit a neutral trend (category a2). Meanwhile, Group 2 includes 21 countries where the process carbon emissions are still increasing and have not peaked, but their net emissions trend encompass both peaked (category b1) and non-peaked (category b2) categories, with 4 and 17 countries respectively.

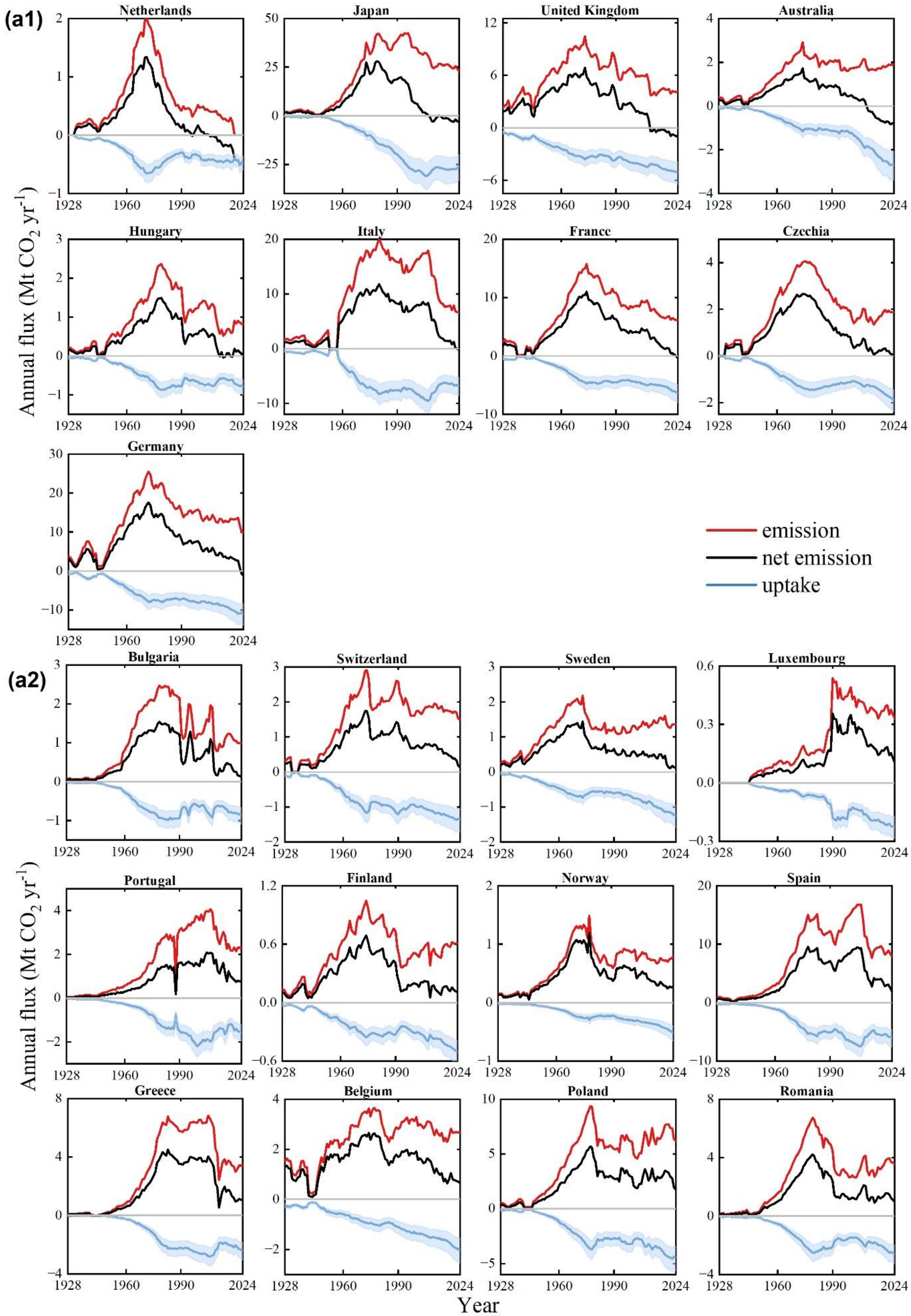
Table 2: List of country classifications.

Groups	Emissions trend	Categories	Net emissions trend	No. of countries
Group1	Peaked	a1	Neutral	9
		a2	Peaked	12
Group2	Non peaked	b1	Peaked	4
		b2	Non peaked	17

Figure 5 shows cement process carbon emissions and uptake for 42 countries from 1928 to 2024. Group 1 (Fig. 5a) predominantly comprises European countries, which were early producers and consumers of cement. In category a1 countries, carbon emissions from cement production have peaked and followed a steady decline, but carbon sinks from cement consumption in these countries have not decreased, resulting in the net-zero or even negative emissions with increasing uptake. For instance, the cement process emissions in Australia peaked at 2.91 Mt in 1974 and then decreased at an average rate of 0.8%. While its cement carbon uptake was 1.17 Mt in 1974 (offset level 40.3%) and then continued to rise, especially from 2000 to 2024, with an average increase rate of 3.3%. By 2009, net cement emissions had turned negative with -0.02 Mt CO_2 yr^{-1} and reached -2.7 Mt CO_2 yr^{-1} in 2024. This is due to the fact that, despite Australia produce less clinker than they used to, their cement consumption has not deceased through substantial clinker imports, with import penetration ratio of 52.8% in 2023. Countries like Netherlands, Japan, United Kingdom, Hungary, Italy, France, Czech and Germany have exhibited similar trends. In category a2 countries, the net emissions are not yet neutralized, but offsets from cement carbon sequestration effectively reduce actual cement emissions. For instance, in most category a2 countries like Sweden, Luxembourg, Finland, Norway and Belgium, the increase in cement carbon uptake outpaces the growth in process carbon emissions, leading to a rapid decline in net emissions after peak year.

In Group 2 countries (Fig. 5b), the cement process emissions have not peaked. However, net emissions have peaked in category b1 countries, such as USA, South Korea, Austria and Denmark, due to carbon sequestration by cement consumption. For instance, a constant demand for cement in USA, process carbon emissions are expected to reach 39.57 Mt CO_2 in 2024. However, as the leading importer of cement, USA has shown a peaked trend in net emissions when considering the carbon uptake of cement consumption. Specifically, from 2009 to 2024, the average carbon offset level in USA has been 89.0%. The non-peaked countries (category b2) are primarily developing countries, and their cement production and consumption have expanded significantly, albeit later than Group 1 countries. China, India, Vietnam, Iran, and Indonesia are notable examples, having experienced rapid growth in cement demand after the 1980s. The cumulative carbon uptake from cement in these countries between 1980 and 2023 accounts for more than 95% of their totals from 1928 to 2023. Notably, Saudi Arabia has recently witnessed a sharp increase, with 39.21 Mt of cement CO_2 uptake in 2023, an increase of 1.7-fold compared to 2020, likely due to its recent economic diversification policies. Due to the higher production and lower imports in category b2 countries, the trends in process emissions and uptake from cement in these countries are similar, with net emissions increasing in line with the process emissions. It's worth mentioning that some countries in category b2 have shown decreasing trends in recent years. For instance, the cement process emissions in China, Brazil and Ireland have decreased for three consecutive years (2022-2024). However, these decreases primarily stem from the decline in cement production rather than from offsets in cement carbonation sink, as their carbon uptake also show a decreasing trend with projections of -1.1%, -1.1% and -5.0% in 2024, respectively. In summary, the carbon offset by cement CO_2 uptake is more significant in peaked countries than in non-peaked countries. Nowadays, many studies have indicated carbon leakage due to outsourcing from these peaked countries (Allevi et al., 2017; Grubb et al., 2022), our results show that the gap in cement process carbon emissions between countries will further widen if the carbon uptake were taken into account.

There exists a time lag of cement process carbon emissions and uptake among different countries. The majority of Group 2 countries are in the initial phases of cement production compared to Group 1 countries. As shown in Figure 6, the trends in four countries are with comparable cement production levels but vary peak years. Germany and France, which began using cement before 1930, experienced a rapid increase in cement process carbon emissions and uptake during 1950s-1970s, peaking in the 1970s. Korea and Ireland has similar trends, but with about 20-year time lag.


(a1)
Netherlands
Japan
United Kingdom
Australia
Hungary
Italy
France
Czechia
Germany
emission
net emission
uptake
(a2)
Bulgaria
Switzerland
Sweden
Luxembourg
Portugal
Finland
Norway
Spain
Greece
Belgium
Poland
Romania
Annual flux (Mt CO_2 yr^{-1})
Year

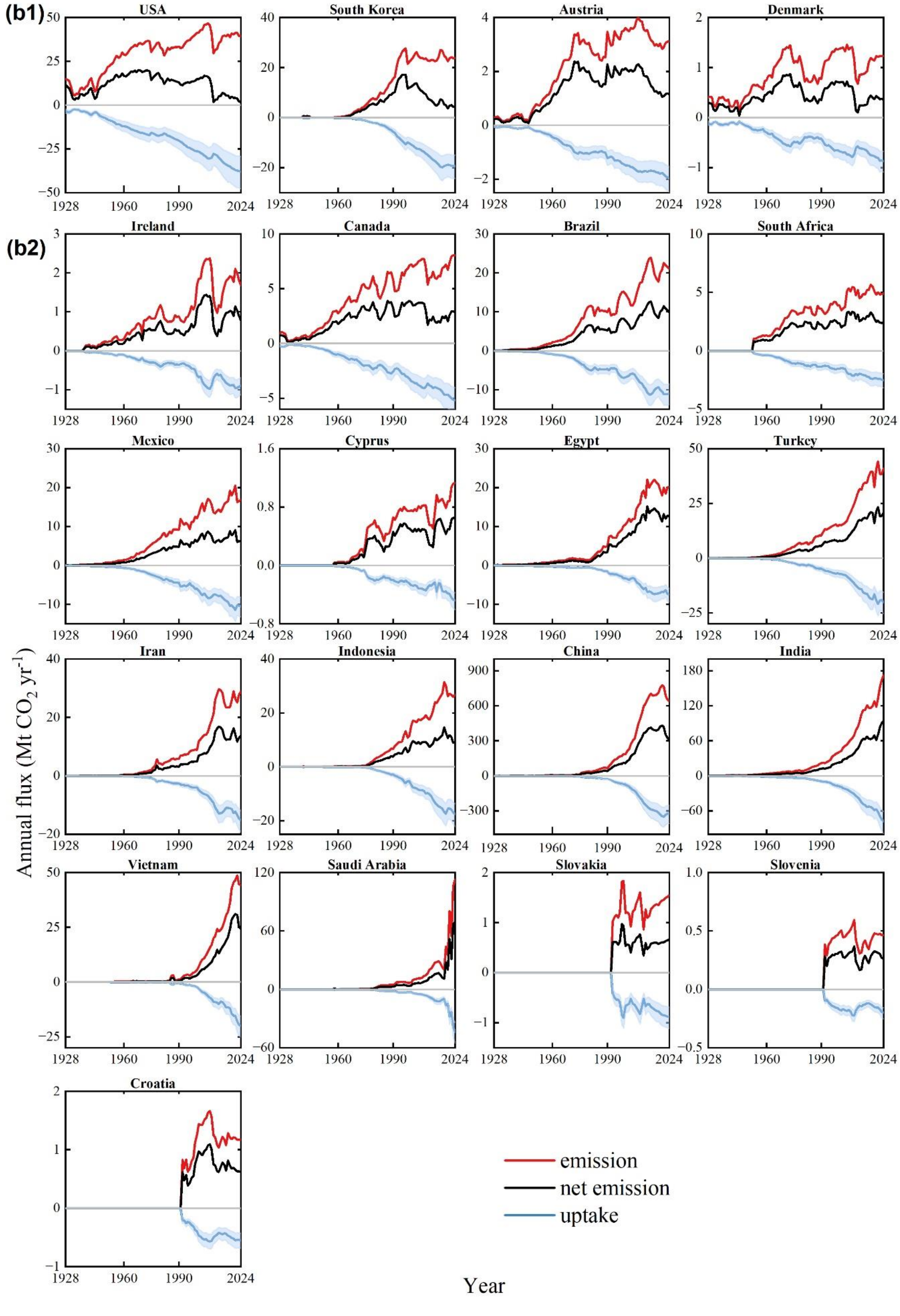


Figure 5: Cement carbon process emissions and uptake in 42 countries during 1928-2024. (a) 21 countries in Group 1 that the cement process emissions have reached peaking. (b) 21 countries in Group 2 with process carbon emissions non-peaked.

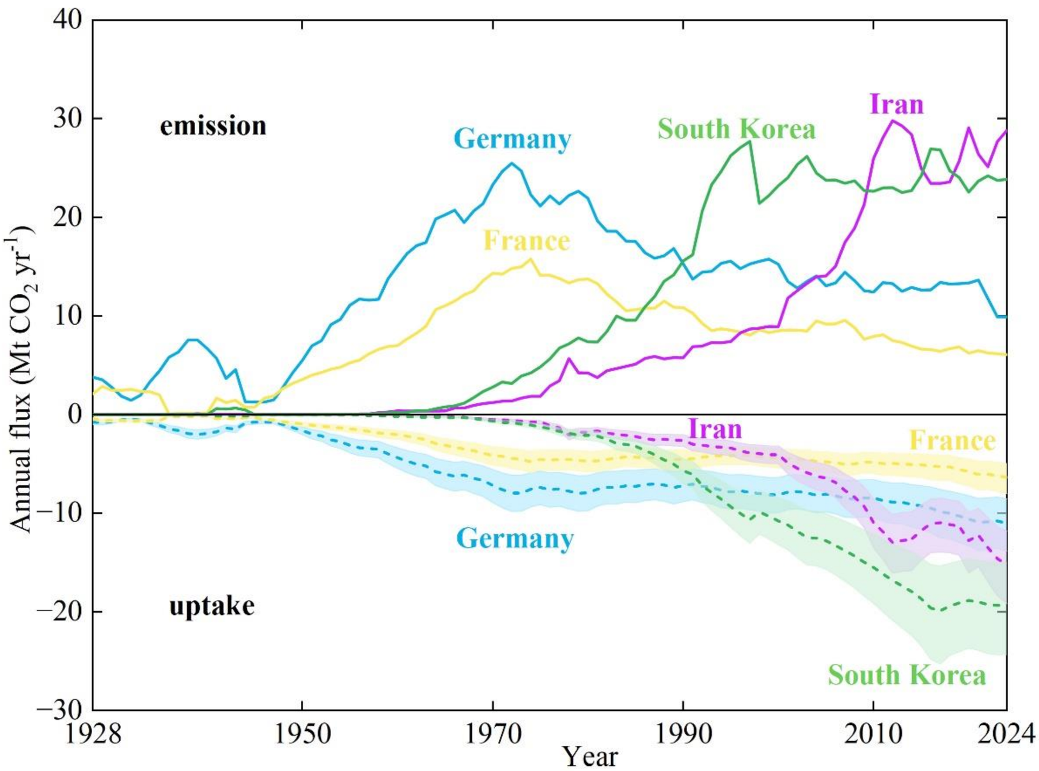


Figure 6: Comparison of trends of process carbon emissions and uptake in peaked and non-peaked countries.

3.4 Uncertainty analysis

This study uses Monte Carlo method to simulate carbon uptake from the cement for 10,000 times to evaluate the uncertainty. The results reveal that the 95% confidence interval for cumulative carbon uptake spanning from 1928 to 2024 ranges from 17.93 to 25.17Gt CO_2. The uncertainties associated with carbon sequestration from cement for each country are detailed in Supplementary Table 4. Our accounting is based on the accounting model of previous research (Huang et al., 2023), where the variable entries and sensitivity value are basically consistent with it (Fig 7). A key difference in our approach is that we have removed the two variables of "the proportion of clinker in cement" and "the ratio of cement consumption to production", because we use a more accurate cement clinker consumption in this study. For specific parameters, "CaO content in clinker" (92.0%) has the greatest impact on the scale of carbon absorption, because it widely affects the carbon absorption in all stages of cement consumption; secondly, "the proportion of cement used for concrete/mortar" and "the proportion of CaO converted to $CaCO_3$ in concrete/mortar", their sensitivity values are 66.4%, and 67.09% respectively, due to these two parameters each affect the whole stage carbon absorption of concrete and mortar, and concrete and mortar account for the largest proportion of the total carbon absorption of cement materials. Other parameters have lower sensitivity values, mostly below 10%, because they only cause a slight impact on the local accounting results of the model. Therefore, it is essential to prioritize the more sensitive parameters and ensure their accurate collection and measurement across different countries to further minimize the uncertainty in the model's accounting results.

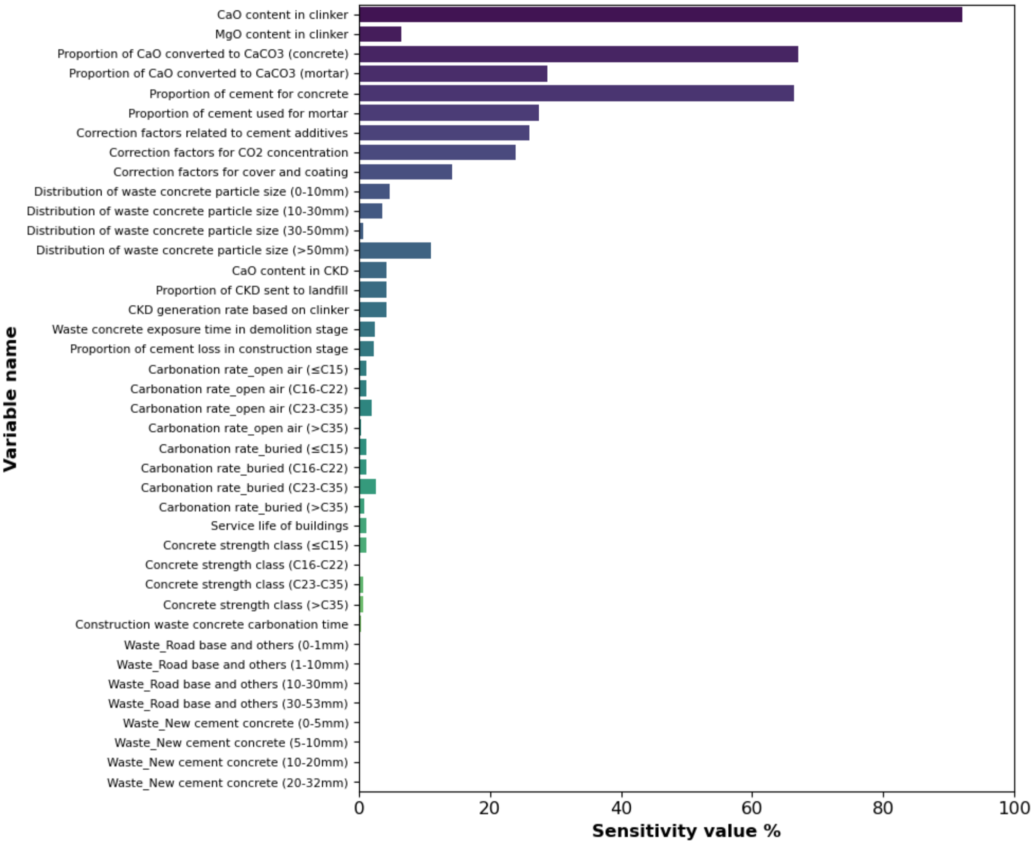


Figure 7: Sensitivity analysis of cement carbon uptake.

4 Data availability

All of the original datasets utilized for estimating cement process emissions and uptake, as well as the results and associated uncertainties in this study, can be accessed on Zenodo at https://doi.org/10.5281/zenodo.14583866 (Wu et al., 2024)

5 Conclusions

In this study, we further advance research on cement carbon uptake accounting system to enrich both temporal scale (1928-2024) and spatial distribution (163 countries and regions) of global cement carbon uptake database, and provide a more accurate bottom-up quantification. Our study reveals that the global and national CO_2 uptake from cement material carbonation cannot be negligible. From 1928 to 2023, global cement materials have absorbed a cumulative total of 21.26 Gt CO_2 (95% CI: 17.93-25.17 Gt CO_2), offsetting 46.1% of the emissions from production process. In 2023, global carbon uptake by cement is 0.83 Gt CO_2 yr^{-1} (95% CI: 0.71-1.00 CO_2 yr^{-1}), with projections for 2024 at 0.86 Gt CO_2 yr^{-1} (95% CI: 0.73-1.02 CO_2 yr^{-1}). The updated national-level databases in this study offer more detailed insights of cement carbon uptake. We find emerging economies are gradually becoming major contributors to global cement carbon uptake since 1982, with increasing cement production, particularly in China and India. In contrast, some Southwest Asian countries have achieved net-zero cement carbon emissions, having been major contributors from 1928 to 1981. Moreover, according to the characteristics of the carbonation kinetic, cement carbonation is a dynamic process, and the share of carbon uptake from historical legacy will gradually increase. It means that the carbon offset by cement carbonation is expected to be more significant in relative terms as cement production decreases in the future, driven by carbon reduction policies across various countries.

The accounting of global carbon uptake by cement is continually improving, and refinements in activity data and carbonation parameters are critical in the accurate carbon sequestration inventory. In this study, we focus on updating the country-specific cement consumption activity data and carbonation parameters based on concrete materials in their service stage, leveraging the extensive civil engineering research available. Considering the increasing demand for cement in emerging economics and their significant contribution to global carbon uptake, optimizing these parameters of these countries in the future study is crucial. It is necessary to refine the carbonation parameters related to concrete demolition and secondary use, as well as other cement products. Especially for cement mortar, which consume less but contribute more to cement carbonation uptake. Efforts should be made to optimize methodological, enabling organisations to rely on better estimates for integrating cement carbonation absorption accounting into national GHG inventories.

Author contributions

LN design the study, collected and assembled the data, prepared, reviewed and edited the manuscript.

SW design the study, conducted modelling, constructed the database, collected and assembled the data.

RMA collected and assembled the data, and revised the manuscript.

ZS collected and assembled the data.

JW revised the manuscript.

FX led the project, design the study, and revised the manuscript.

Competing interests.

The contact author has declared that none of the authors has any competing interests.

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