Response to Reviewers

Manuscript ID: ESSD-2024-437

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

Introduction: We sincerely thank the reviewers for their thorough evaluation and insightful comments on our manuscript. Their constructive feedback has been invaluable in improving the quality and clarity of our work. We have carefully considered each suggestion and made the necessary revisions in the manuscript. Below, we provide a detailed point-by-point response to the reviewers' comments, highlighting the changes implemented in the revised version.

Contents

Reply on CC1

This study presents a updated dataset of global and national carbon uptake by cement carbonation from 1928 to 2024 based on previous studies (Xi et al., 2016; Guo et al., 2021; Huang et al., 2023). The updated dataset of cement carbon uptake covers 163 cement-producing countries worldwide for the first time, and extends the time scale to 1928-2024. Cement carbon sink has shown substantial impacts on the Global Carbon Budget (Friedlingstein et al., 2023, 2022a, b, 2020). While this study reveals the contribution of cement carbon sequestration as a carbon sink in each country, which making it is possible to include cement carbon sink in national GHG inventories (Andersson et al., 2019).

The manuscript is well written, however there are some comments need to be addressed.

Response: We sincerely appreciate your high regard and meticulous review of our manuscript, and your positive feedback has given us great encouragement. We have thoroughly considered your suggestions and rechecked the entire text to enhance the manuscript's quality, as follows in response to your comments.

1. The data description of the article contains supplementary information, including 4 supplementary tables (https://doi.org/10.5281/zenodo.13827861). But it is difficult for readers to find the corresponding relations between the main texts and the data in supplementary tables. It is recommended that manuscripts have clear links to data files in the data description section. For example, in the section “2.1 Data source and treatment”, the explicit table paths should be indicated in corresponding data (Ln.104-118).

   Response: Thanks for your suggestion. There are four tables in the Supplementary tables. Supplementary table 1 is the activity level data of cement clinker production and consumption, which contains five data: (1) cement production, (2) cement clinker ratio, (3) clinker imports, (4) clinker exports, and (5) revised clinker production for countries from 1928 to 2024. Supplementary table 2 is the input model parameters of cement uptake and emissions, including the parameters of cement carbon uptake (Data 1~Data 11), and the carbon emission factors (Data 12) for countries. Supplementary table 3 shows the accounting results of cement carbon uptake, including global carbon uptake by cement material and use (Data 1), annual global carbon uptake by cement material and relevant lag time (Data 2), global carbon uptake by 163 countries and regions from 1928 to 2024 (Data 3) and process carbon emissions from cement production by region and category from 1928 to 2024 (Data 4). Supplementary table 4 is the result of uncertainty accounting for global and national carbon uptake in cement.
   Changes: We have added a description of the detailed indexing of Supplementary tables. The changes are reflected on Lines 127-128, 187, 198 and 268-269 in the revised manuscript.

2. Figure 1c, 1e, and Figure 3, “uptakes” should be “uptake”.

   Response: Thanks for your comments. We have changed the “uptakes” in figure 1 and figure 3 to “uptake”.
   Changes: In the revised manuscript, we have changed “uptakes” to “uptake” in the title of the axis coordinates of Figure 1, and in the figure notes of Figure 3.
3. It is recommended that “emission” in the text should be “process emission”, where the emission from energy consumption in cement industry was process emission.

   Response: Thank you for your rigorous consideration. According with your advice, we have changed the expression “emission” from cement production process in the original text to “process emission”.

Changes: The changes are reflected on Lines 90, 182, 218, 231, 266, 329-222, 337, 341, 349, 353, 362, 369, 371, 374, 378-381, and 401 in the revised manuscript.

4. Why are the global cement carbon sinks in 2023 and 2024 in this study smaller than that of 2021 in previous study (Huang et al., 2023)? Please explain it more clearly.

Response: Thank you for your valuable comments. It's important to note that of the estimate of global cement carbon uptake in this study is not merely updating three years of data from previous studies. Instead, we have employed a bottom-up approach to calculate global carbon uptake. The cement carbon uptake for 2021 in this study is 0.83 Gt CO_2 (95 % CI: 0.70-0.99 Gt CO_2 yr^{-1}). While this is slightly lower than the 0.96 Gt CO_2 (95 % CI: 0.81-1.15 Gt CO_2 yr^{-1}) reported in the previous study (Huang et al., 2023), it falls within the uncertainty range of the earlier estimate. This is mainly due to the fact that the activity level data in this study is corrected cement consumption. The global cement carbon uptake in 2022 is 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, the global cement carbon uptake is 0.84 Gt CO_2 (95 % CI: 0.71-10.03 Gt CO_2 yr^{-1}), an increase of 2.8 % 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: 0.73-0.99 Gt CO_2 yr^{-1}), marking an increase of 2.0 % from the 2023 levels.

Changes: We have added the description to Lines 235-243 of the revised manuscript. "The results show that global cement carbon uptake in 2022 is 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."

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Reply on RC1

General Comment

The manuscript, ESSD-2024-437, represents the fourth update of the Global Cement Carbon Uptake Database. Compared to previous versions, this update enhances the records to the country level, extends the temporal coverage, and reduces uncertainty by focusing on cement clinker production rather than apparent consumption. The manuscript is well-written, and I believe such an update is valuable to the community. Below, I have outlined several comments that may help improve this work.

Response: We are sincerely appreciated of the valuable comments and suggestions provided by the reviewer. Those comments are all valuable and very helpful for revising and improving our paper, as well as the important guiding significance to our researches. We have carefully revised the paper according to the reviewer' comments and provided comprehensive explanation of the revisions made to the manuscript and offered a point-by-point response.

Major Comments

1. **Forecasting for 2024**

   The ARIMA temporal forecasting model is commonly applied when data series exhibit high autocorrelation, such as seasonal cycles. However, the annual production and carbon uptake data in this study are strongly influenced by economic development and policy-making in one specific year, leading to high variability (as shown in Figure 4). How do the authors justify the use of ARIMA in this context?

   Response: Thank you very much for your comment. The ARIMA model is one of the valuable projecting techniques in forecasting to the upcoming events in time series analysis. The model is particularly effective for modeling temporal dependencies and forecasting when there is significant autocorrelation, even in the presence of high variability. This model has been widely used for forecasting production in various industries, including oil (Ning et al., 2022), gold (Mutele and Carranza, 2024), and fossil fuels (Ediger et al., 2006), and its applicability has been validated through comparisons with other forecasting models. In this study, as you are concerned, cement production is influenced by economic and policy, but we used a longer time series (1928-2023) to forecast production for 2024, which extended dataset allows the model to account for both short-term fluctuations and long-term trends, enhancing the robustness of the forecast. Furthermore, the differencing process ARIMA model reduces the impact of external factors by removing long-term trends from the data. To further validate the model, we conducted forward-chained cross-validation by progressively rolling the training set forward, evaluating the model's predictions at each step, and calculating the root mean square error (RMSE) for each forecast. We then compared the average of all the RMSE values with the standard deviation (SD) of the time series data. Generally, RMSE values exceedingly twice the SD suggest that the model's predictions are less reliable. Our results show that the ratio of RMSE to SD for each country ranges from 0.022 to 0.516, indicating that the models exhibit relatively small errors. The following Table 1 illustrates the validation of the model for 42 countries, with information on the remaining countries provided in SI data 1 in Supplementary table1.

Table 1: Summary of ARIMA models and their cross-validation results for 2024 cement production forecasts for 42 countries

Code	ISO	Countries	ARIMA Method	RMSE	SD	RMSE/SD

1	AUS	Australia	ARIMA (0,1,0)	244.10	3179.1	0.077
2	AUT	Austria	ARIMA (1,1,0)	208.79	1950.2	0.107
3	BEL	Belgium	ARIMA (2,1,3)	505.73	2198.4	0.230
4	BGR	Bulgaria	ARIMA (0,1,0)	214.04	1786.4	0.120
5	CAN	Canada	ARIMA (0,1,1)	636.66	4631.6	0.137
6	HRV	Croatia	ARIMA (0,1,0)	103.72	1331.4	0.078
7	CYP	Cyprus	ARIMA (1,1,0)	79.11	627.4	0.126
8	CZE	Czechia	ARIMA (0,1,0)	624.55	3299.5	0.189
9	DNK	Denmark	ARIMA (0,1,0)	177.17	741.1	0.239
10	FIN	Finland	ARIMA (0,1,0)	115.70	553.2	0.209
11	FRA	France	ARIMA (0,2,1)	995.70	8976.8	0.111
12	DEU	Germany	ARIMA (0,1,0)	2193.67	13967.9	0.157
13	GRC	Greece	ARIMA (0,1,0)	508.48	5753.4	0.088
14	HUN	Hungary	ARIMA (0,1,1)	561.58	1698.3	0.331
15	IRL	Ireland	ARIMA (1,0,0)	477.69	2250.5	0.212
16	ITA	Italy	ARIMA (0,1,0)	1978.69	15521.0	0.127
17	LUX	Luxembourg	ARIMA (2,1,2)	36.31	394.3	0.092
18	NLD	Netherlands	ARIMA (0,1,0)	173.91	1282.7	0.136
19	NOR	Norway	ARIMA (2,1,2)	126.16	726.9	0.174
20	POL	Poland	ARIMA (0,1,0)	869.71	6756.4	0.129
21	PRT	Portugal	ARIMA (1,1,0)	592.86	3514.8	0.169
22	ROU	Romania	ARIMA (0,1,0)	563.89	4762.6	0.118
23	SVK	Slovakia	ARIMA (0,1,1)	228.89	1575.7	0.145
24	SVN	Slovenia	ARIMA (1,1,0)	62.46	489.6	0.128
25	ESP	Spain	ARIMA (1,1,0)	1297.60	13601.9	0.095
26	SWE	Sweden	ARIMA (0,1,0)	167.96	927.1	0.181
27	CHE	Switzerland	ARIMA (1,1,0)	230.72	1650.4	0.140
28	GBR	United Kingdom	ARIMA (0,1,1)	784.47	3841.1	0.204
29	USA	USA	ARIMA (0,1,1)	3591.85	24688.3	0.145
30	MEX	Mexico	ARIMA (0,1,1)	1047.13	15544.8	0.067
31	BRA	Brazil	ARIMA (4,1,0)	1405.55	21850.8	0.064
32	EGY	Egypt	ARIMA (3,2,1)	1198.08	18044.4	0.066
33	TUR	Turkey	ARIMA (2,2,2)	1764.20	25147.4	0.070
34	IRN	Iran	ARIMA (1,1,0)	1319.29	21925.7	0.060
35	SAU	Saudi Arabia	ARIMA (2,1,3)	1137.73	18218.0	0.062
36	IND	India	ARIMA (0,2,1)	3749.43	105504.2	0.036
37	CHN	China	ARIMA (0,2,2)	29719.75	801120.9	0.037
38	KOR	South Korea	ARIMA (0,1,1)	1427.65	22713.0	0.063
39	JPN	Japan	ARIMA (1,2,2)	2550.74	31584.8	0.081
40	VNM	Vietnam	ARIMA (1,2,1)	1291.98	30389.8	0.043
41	IDN	Indonesia	ARIMA (2,2,3)	1177.49	21676.9	0.054
42	ZAF	South Africa	ARIMA (0,1,0)	436.09	4640.0	0.094

Changes: We performed cross-validation on the ARIMA forecasting model applied to 163 countries and included the results in the Supplementary tables (available from https://doi.org/10.5281/zenodo.14583866 Wu et al., 2024), with corresponding descriptions provided in the main text: "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)."

2. **CO_2 Uptake Characteristics**

The CO_2 uptake ability of concrete theoretically decreases significantly over time due to surface calcification. How does the CO_2 uptake model (Table 1) account for this characteristic? Including explicit figures to demonstrate this phenomenon would strengthen the analysis.

Response: Thank you very much for your valuable comments. The ability of concrete to absorb CO_2 does decrease significantly with surface calcification. Our carbon uptake model is primarily based on Fick' s second diffusion law, as proposed by civil engineering researchers (Andersson et al., 2013). According to this principle, the depth of carbonation (*d*) is proportional to the product of the carbonation rate (*k*) and the square root of the exposure time (*t*) (see Eq. (8) in the manuscript).

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

This model has been verified by many experimental studies (You et al., 2022), Figure 1 shows that the overall carbonation depth of the cement under different treatment is linearly related to the square root of time, with correlation coefficients above 97%.

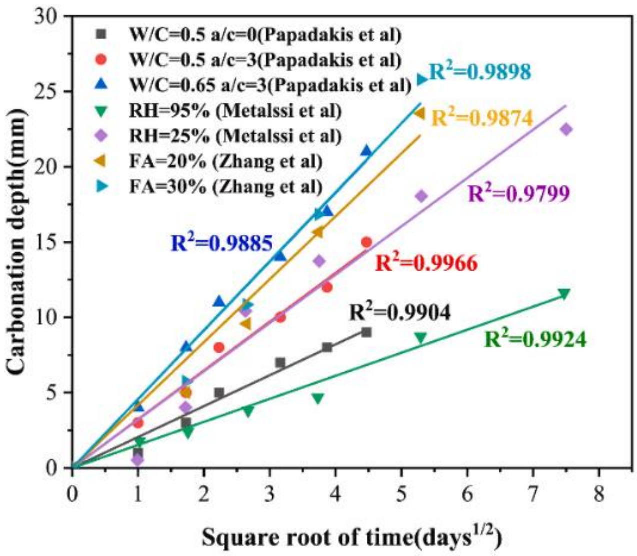


Figure 1. The relationship between carbonation depth and square root of time. W/C: water-cement ratio; a/e: aggregate-cement ratio; RH: relative humidity; FA: the dosage of fly ash (source: You et al., 2022. DOI: 10.1016/j.cemconcomp.2021.104315)

This empirical model is further adapted based on the type of concrete used in the CO_2 uptake model (Table 1 in Manuscript). Under this framework, the carbonation depth of cementitious materials is tied to the square root of their exposure time, meaning the annual rate of carbonation slows over time. The connotations of the model have been fully explained in our previous studies, and details can be found in the Methods part and Supplementary Figure 3 in Xi et al (2016). Considering that this study is mainly further update of the result of cement carbon uptake, the methods part is not repeated. However, as you mentioned in your comment, we have further refined the results to better demonstrate this feature. Specifically, we have included the time-lag data for cement carbon uptake in the supplementary data file (SI data 2 in SI table 3). The Figure 2 below highlights the time-lag effect on carbon uptake by cement from 1928 to 2024 (it is a refinement of the historical year carbon uptake in Figure 1e in the manuscript). As shown, the carbon uptake of the same batch of cement materials gradually decreases over time. For example, the carbon sequestration from global cement consumption in 1990 amounted to 121.0 Mt CO_2 during that year, whereas by 2023, the sequestration from the same cement has decreased to only 2.0 Mt CO_2.

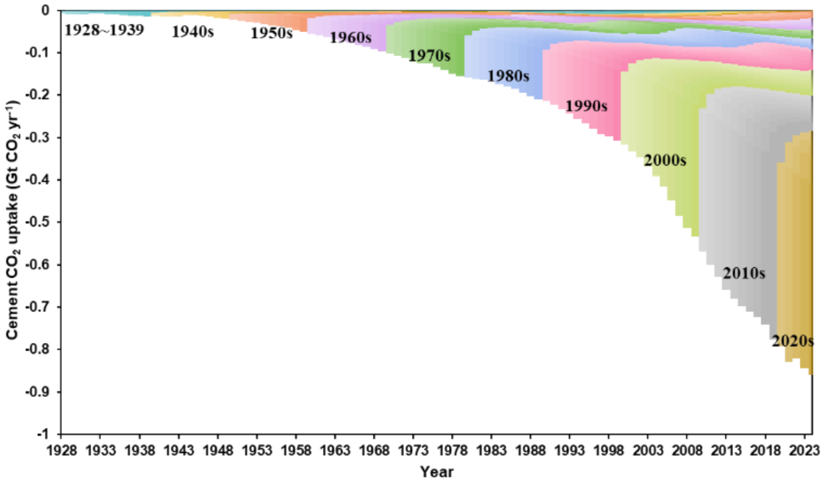


Figure 2. Time-lag effect on carbon uptake by cement from 1928 to 2024. Different colours represent changes in carbon sequestration over time for different years of consumption of cement.

Changes: We have added year-by-year data on carbon sequestration by cement materials to the supplementary results file to demonstrate the time-lag effect (SI data 2 in Supplementary table 3, available from https://doi.org/10.5281/zenodo.14583866 Wu et al., 2024). And we have added the reference to the method explanations in Section 2.3 (see Line 146 in revised manuscript). Furthermore, we have included Figure 2 along with its description in Section 3.1 of the revised manuscript: "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." The new section can be found on page 12, Lines 281-286.

3. **Input Data Summary**

It is recommended to summarize the metadata of input data (e.g., time span, resolution, references, and data links) in a table for ease of reference.

Response: We sincerely appreciate the detailed review and insightful suggestion. There are two input data tables in the Supplementary tables (SI table1 and SI table2), they are activity level data and cement uptake parameters, respectively. We've added the summary of the data to the front of these tables based on your suggestion.

Changes: We change the "Index" table in the Supplementary tables (available from https://doi.org/10.5281/zenodo.14583866 Wu et al., 2024) to a "Summary" table containing a summary of the input data information.

4. **Figure 1b**

The carbon offset levels in Figure 1b show a clear overall increasing, stable, trend (unit as percentage) over the past 100 years. Considering the construction substantially increased over the past century, does this indicate that the carbon uptake efficiency of materials is increasing over time? I did not follow. Additionally, uncertainty levels should be provided in this figure. The explanation of short-term disturbances, such as World War II, is reasonable, but the manuscript lacks interpretation for the long-term stable increase in carbon offset levels.

Response: Thank you very much for your helpful comment. Firstly, the steady increase in the offset level in Figure 1b does not imply that the rate of cement carbon uptake is necessarily increasing. In this figure, the offset level represents the ratio of global cement carbon absorption to cement carbon emissions. Since the activity level data of cement carbon uptake and carbon emission are all based on the consumption of cement clinker, the offset level seems to be related to the ratio of the carbon uptake parameters to the emission factor only. However, it is important to note that the accounting for cement carbon sequestration differs from that of cement carbon emissions (calculated as activity level data × emission factors). The key distinction lies in the fact that cement materials, particularly concrete, cannot fully carbonate within a single year. As a result, cement carbon sequestration exhibits a time-lag (Figure 2) relative to carbon emissions. In other words, cement carbon sequestration accumulates gradually over the years, unlike carbon emissions from cement production process which occur instantaneously. This is the primary reason for the steady increase in cement carbon offsets over time. Furthermore, since the carbon offset level in this figure is defined as the ratio of carbon sequestration to carbon emissions for cement, its uncertainty inherently stems from the uncertainties in both carbon sequestration and carbon emissions. However, determining the uncertainty of this ratio does not seem to have a significant or disproportionate impact on decision-making or practical applications. Therefore, this study prioritizes the quantification of carbon sequestration and the interpretation of its uncertainty, rather than overemphasizing the uncertainty of the offset ratio itself.

Changes: We have included an explanation of the long-term stable increase in carbon offset levels in the section 3.1 of the manuscript. "Unsurprisingly, the carbon offset level (uptake-to-emission 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." The change can be found on page 10, Lines 226-229.

5. **Discussion on Cement Carbonation Risks**

Page 10, Line 237: The authors call for inter-industry collaboration to maximize CO_2 uptake from cement materials. While this is an important goal, it is worth noting that cement carbonation significantly reduces the durability of constructions. Reconstruction necessitated by reduced durability would lead to additional carbon emissions. Could the authors discuss the potential risks associated with relying on carbonation as a pathway to achieving carbon neutrality?

Response: We are especially thankful for your detailed feedback on cement carbonation risks, which has been very helpful. Carbonization of cement materials does significantly reduce the durability of buildings (Zhang et al., 2025). According to Huang et al. (2024), the carbon emissions from the production phase of building materials and the construction phase account for 15.6% and 1.6% of their full life cycle, respectively. Therefore, we can’t reconstruct just to enhance the carbon absorption capacity of cement which exacerbate the risk of increased emissions. Instead, we should focus on extending the lifespan of buildings to align with advancements in engineering technology. For instance, the average building lifespan in some European countries is currently around 70 years, approximately 65 years in the United States, but only 35 years in China (SI data5 in Supplementary table 2, available from https://doi.org/10.5281/zenodo.14583866 Wu et al., 2024). Moreover, further research remains necessary to identify appropriate scenarios for departmental application. For example, Ostovari et al. (2021) analyzed the carbon footprint of the combined CO_2 mineralization and cement production based on life cycle assessment, and showed that integrating CO_2 mineralization with cement production has the potential to transform the cement industry from an unavoidable CO_2 source to a CO_2 sink. Given mineralization of cementitious materials as an important carbon neutral pathway, it is essential to evaluate its emission reduction potential and associated risks before implementing it in practice.

Changes: In order to avoid misunderstandings in the presentation, we have changed the presentation in the section 3.1: “The significant carbon sequestration of cement materials makes them one of important carbon sinks in the global carbon cycle. Moreover, the potential of carbon capture, utilization and storage (CCUS) can contribute 36 % of the reduction for the cement industry to achieve net-zero emissions (IEA, 2024). Many studies have explored the mechanisms and properties of accelerated carbonation in cement materials, including concrete (Alshalif et al., 2021, 2022), cement paste (Castellote et al., 2008; Morandeau et al., 2015), slag cement (Mo and Panesar, 2013), and CKD (Pu et al., 2023). Ostovari et al. (2021) demonstrated that integrating CO_2 mineralization with cement production has the potential to transform the cement industry from an unavoidable CO_2 source to a CO_2 sink. 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.”

6. **Comparison with Previous Studies**

As this study is an update of Huang et al. (2023) with some shared figures but updated results, it would be helpful to include an explicit comparison with previous reports. Are there any revised conclusions, corrections, or new insights presented in this update?

Response: Thank you for your valuable comments and suggestions. In Section 2.2 of the manuscript, we provide a detailed discussion of the improvements made in this study compared to the previous research (Huang et al., 2023). As mentioned in the manuscript, the key update of this study focuses on a more refined analysis of cement carbon sequestration across different countries worldwide. While the earlier version only covered the United States, China, India, and European countries (Xi et al., 2016; Guo et al., 2021; Huang et al., 2023), this study first expands the scope to include 163 countries. This refinement in country-level accounting for cement CO_2 uptake allows us to uncover trends in the global distribution of carbon sequestration by cement materials over nearly a century. Furthermore, we analysed the emission reduction characteristics of cement carbon sequestration in various countries, revealing that 21 countries have already achieved carbon neutrality in cement production. These findings represent one of the most significant new contributions of our study and is highlighted in Sections 3.2 and 3.3 of the manuscript.

Accounting for global cement carbon sequestration has been a primary goal of our research. In this study, we have expanded the time span of the global cement carbon sequestration database from the previous period of 1930 to 2021 to cover 1928 to 2024. Compared to global cement carbon uptake in 2021, our findings show a decline in 2022 and 2023, with respectively reductions of 1.1% and 2.8% from the previous year. However, global cement carbon uptake in 2024 is expected to experience a slight rebound, driven by strong market activity in Southeast Asia and Africa (Cheng et al., 2023), with an estimated increase of around 2.0% compared to the previous year.

In addition, this study calibrates cement clinker consumption, therefore two variables were excluded from the original model—the proportion of cement clinker and the ratio of cement consumption to production. This adjustment helps to reduce the uncertainty associated with these variables. This point is mentioned in the newly added section on uncertainty analysis.

Changes: We have added the description to section 3.1 of the revised manuscript. “The results show that global cement carbon uptake in 2022 is 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.” The new section can be found on page 10, Lines 234-242.

7. **Uncertainty and Future Directions**

Adding a dedicated section or paragraph to discuss data uncertainty and propose potential research directions would enhance the manuscript.

Response: Thanks very much for your opinion. The accounting results in this study are based on 10,000 Monte Carlo simulations, providing 95% confidence intervals for cement carbon absorption estimates across various materials, individual countries, and on a global scale (see Supplementary table 4). According to your suggestion, we conducted sensitivity analyses on the model parameters to clarify the impact of each parameter, offering valuable references for improving the accuracy of future accounting results.

Changes: We have added section 3.4 “Uncertainty Analysis” to discuss data uncertainty: “This study uses Monte Carlo method to simulate carbon uptake from the cement for 100,000 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%, 27.5%, 67.09% and 28.72% 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.” The new section can be found on page 14, Lines 382-399.

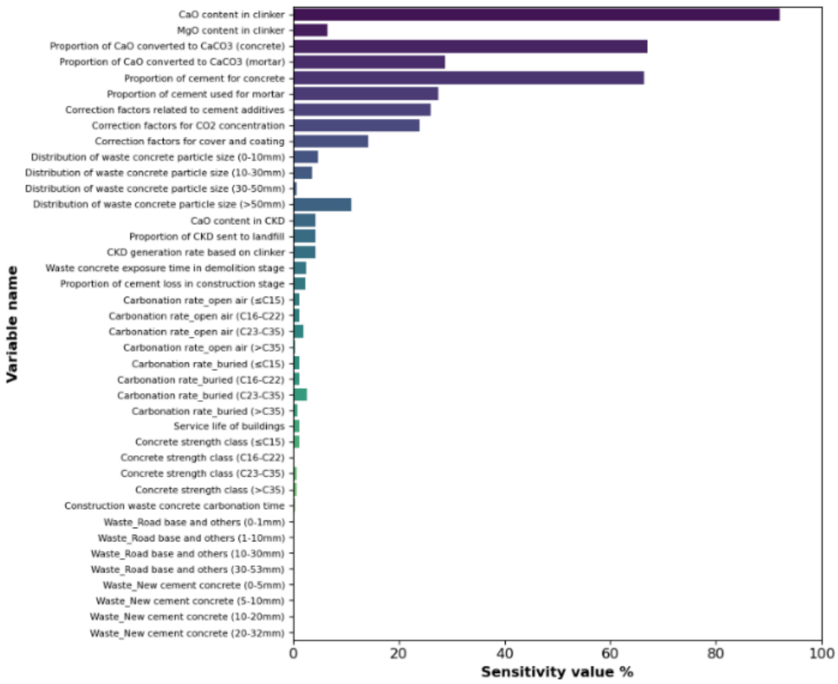


Figure 7: Sensitivity analysis of cement carbon uptake.

Minor Comments

1. **Page 2, Line 48**: The manuscript refers to cement carbonation as a "permanent CO_2 uptake method." Given that the carbon uptake ability changes over time, why is it characterized as permanent?

Response: Thank you for your valuable comment. The term “permanent” in the manuscript refers to the long-term sequestration of CO_2, meaning that once CO_2 is fixed in a substance or geological stratum through mineralization or geological sequestration, it remains stable over time and is not released back into the atmosphere.

Changes: To avoid any misunderstanding, we have removed the statement from this section in the original text.

2. **Page 2, Line 55**: This report suggests a nearly 50% uptake from cement carbonation, which differs significantly from the 10% uptake reported by PCA. Could the authors explain this discrepancy?

   Response: Thanks very for your careful review. The significantly larger of cement CO_2 uptake offsets level in this study (46%) compared to the value (10%) in Portland Cement Association (PCA) of the United States can be attributed to the difference in accounting scope. While the PCA report only includes the carbon sequestration of concrete, our analysis covers a broader range of cement materials, including four types: concrete, mortar, construction waste materials, and cement kiln dust (CKD). In our result, the global carbon uptake from concrete materials accounts for approximately 15.4% of the total emissions from cement production (averaged over the past 100 years), which aligns with the findings in the PCA report. Notably, mortar emerges as the largest contributor to carbon sequestration, accounting for 48% of the total. However, due to limited data and model constraints, few studies have focused on mortar, representing an area for future optimization of our model, as discussed in the Outlook section of the manuscript.

   Changes: We have emphasized in the manuscript where we introduced the PCA report that he was referring only to concrete materials: "…, 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)". The changes are reflected on page 2, Lines 56-58.

3. **Page 3, Line 79**: Citing the previous three updates of the Global Cement Carbon Uptake Database in this section would help readers better understand the evolution of the dataset.

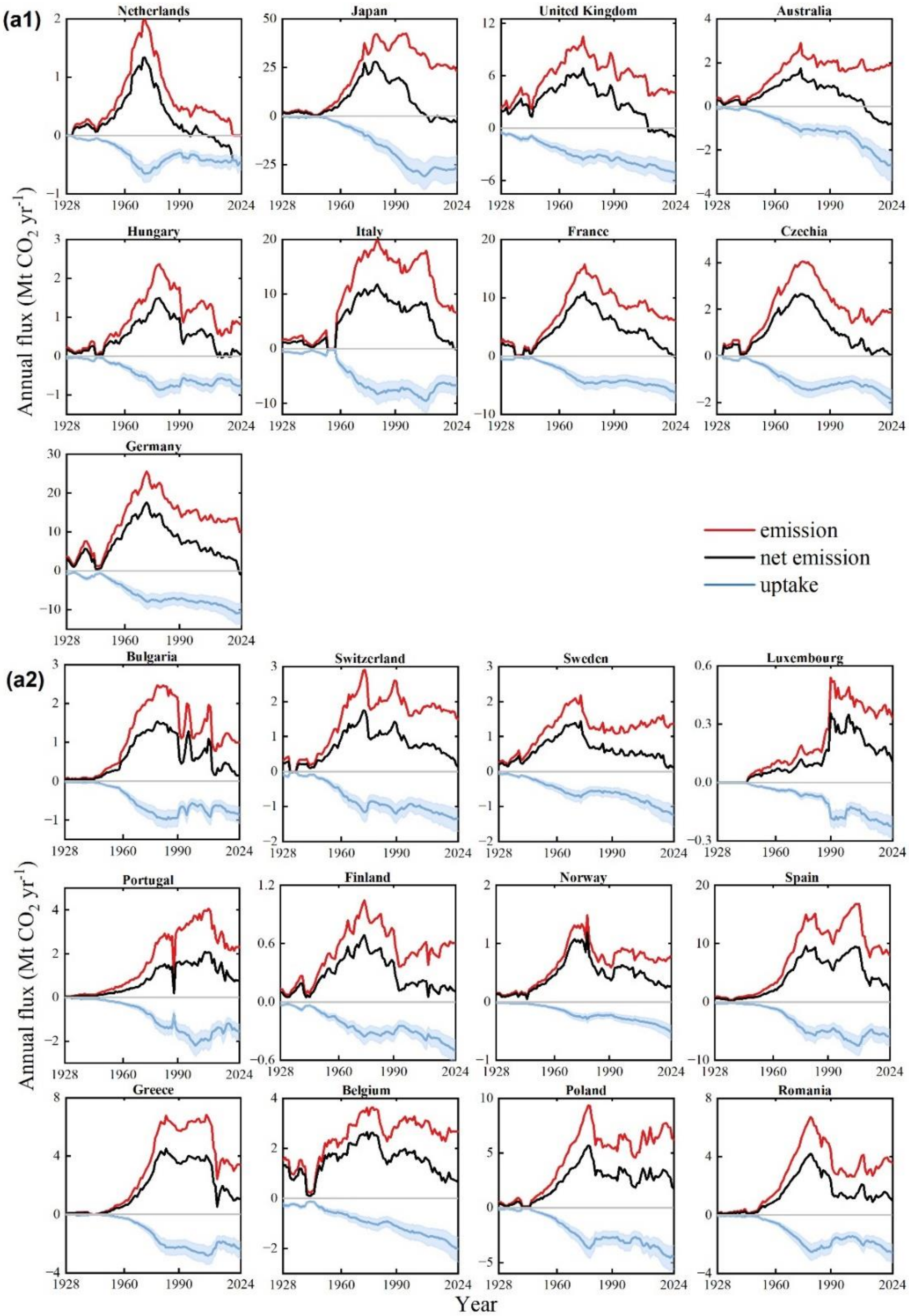
   Response: Thanks very for your careful review. The previous three database are Xi et al., 2016; Guo et al., 2021; Huang et al., 2023, respectively. We have cited them in the manuscript as you suggested.

   Changes: We have added the citation of the previous database in the manuscript. The changes can be found on page 3, Line 83.

4. **Figure 4 & 5**: provide full spells of the countries in Appendix or supplement would be helpful. Any possibility to include the uncertainty range?

   Response: Thank you very much for your suggestion, we have changed the abbreviation of the countries name in the Figure 4 to the full spelling and increased the uncertainty of the carbon uptake, the detailed data can be found in the Supplementary table 4 (available from https://doi.org/10.5281/zenodo.14583866 Wu et al., 2024).

   Changes: We have changed the figures as you suggested to the following:


(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

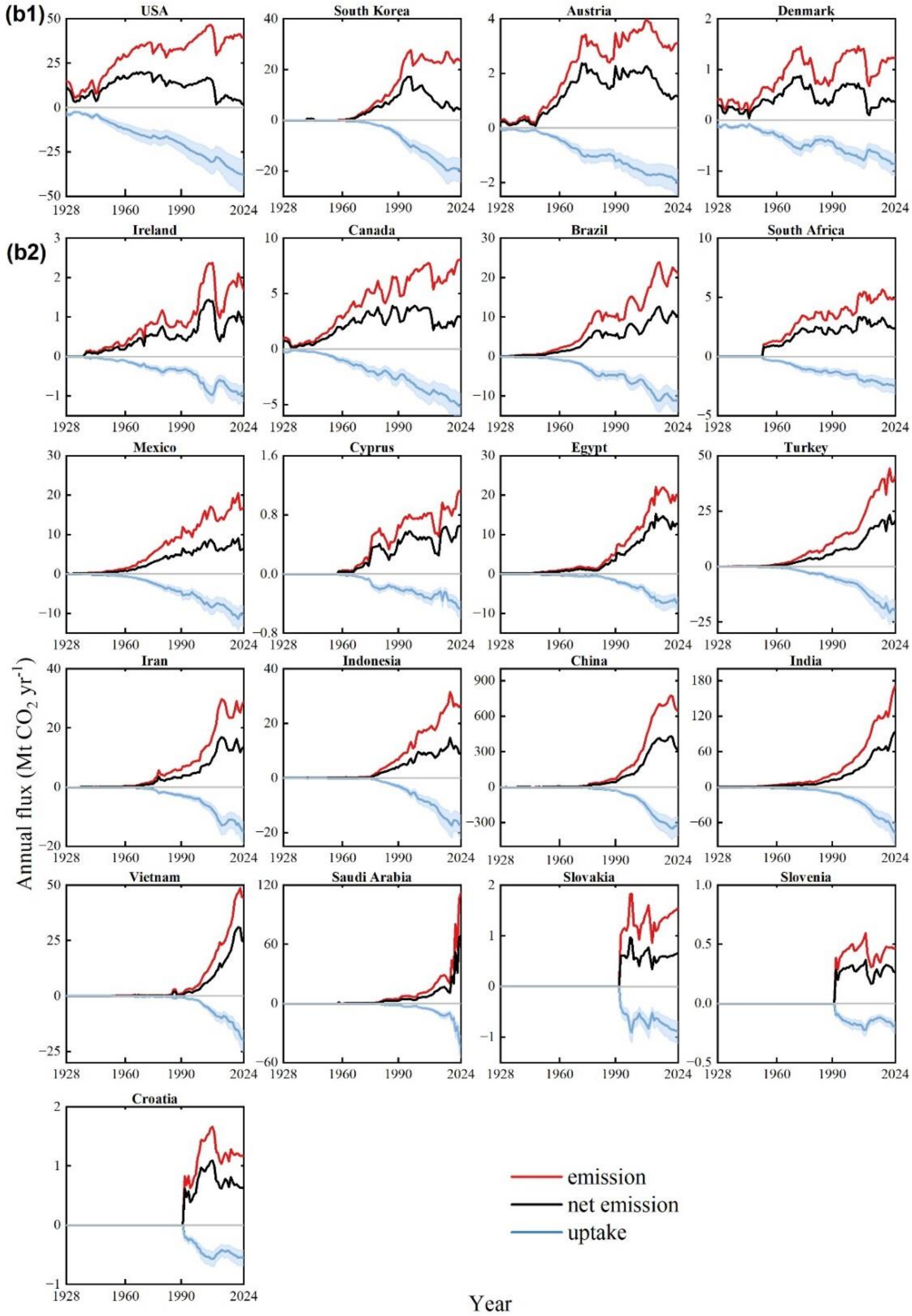


Figure 4: Cement carbon process emission and uptake in 42 countries during 1928-2024. (a) 21 countries in Group 1 that the cement process emissions have reached peaking. (b) 21 countries in Group 2 with process carbon emissions non-peaked.

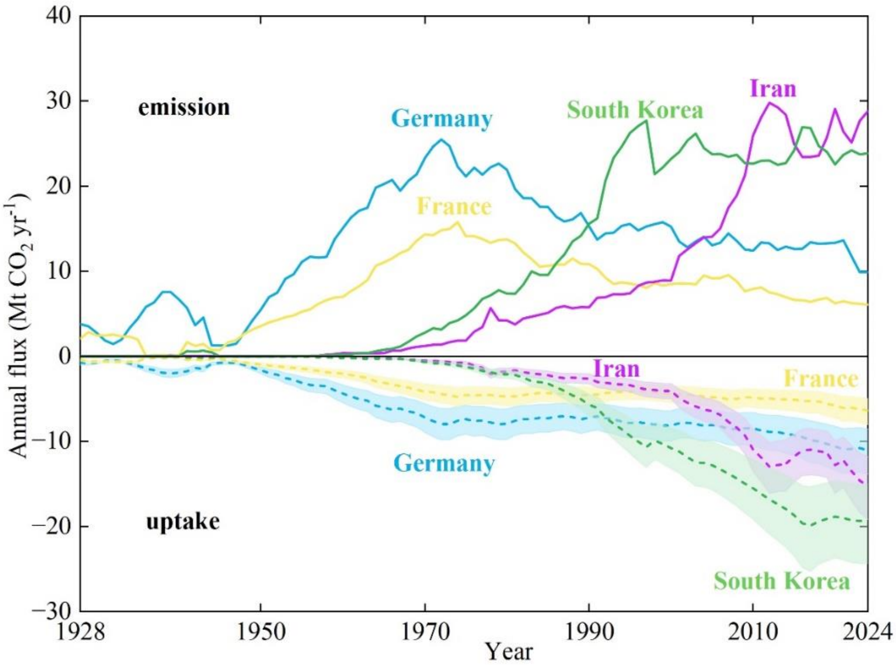


Figure 5: Comparison of trends of process carbon emission and uptake in peaked and non-peaked countries.

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Reply on RC2

Reading this paper leaves me with the impression that they have probably done the analysis properly but it leaves me with many questions where the details are not sufficiently clear. Let me walk through the text and point our specific questions.

Response: Your expert review has been of great assistance in enhancing the scientific rigor and clarity of our work. We are truly thankful for your contribution. We have carefully revised the paper according to the reviewer' comments and provided comprehensive explanation of the revisions made to the manuscript and offered a point-by-point response.

Line 36: I think we could use another sentence to make clear that there are 3 "types" of emissions discussed in this paper. Fossil fuel emissions, chemical process emissions, and the net emissions which are the sum of chemical process emissions and chemical uptake.

Response: We are grateful for your review. Your insight is correct, and it is necessary to provide a definition of net emissions to make it clearer for the readers. The emissions for the cement industry include both fossil fuel emissions and chemical process emissions. This study emphasizes the CO_2 sequestration by the cement. Therefore, we propose the definition of net emissions to reflect process emissions after deducting of cement carbon sequestration. This definition has been mentioned in previous studies (Xi et al., 2016). We have added it at the application of line 47 of the original text.

Changes: we have added the definition of "net emission" in revised manuscript: "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 (namely industrial process of cement production minus the CO_2 sequestration from carbonation of cement materials) were only about 57% of the cumulative process emissions from 1930 to 2013 (Xi et al., 2016)." The changes can be found on page 2, Lines 47-49.

Line 38: cites emissions for 2023 from a paper that was published in 2019?

Response: Thank you for your thoughtful comment. The article cited in here is "Andrew, R.M., 2019. Global CO_2 emissions from cement production, 1928–2018. Earth System Science Data 11, 1675–1710. https://doi.org/10.5194/essd-11-1675-2019." This article published in 2019 and presents global cement process carbon emissions from 1928 to 2018, the data is available at https://zenodo.org/records/11207133, The database is updated annually, with the latest version released in May 2024. The new data covers global cement process carbon emissions from 1880 to 2023. However, the citation for the data remains (Andrew, 2019).

Line 48: It seems to me that this uptake is discussed several times in the paper without recognizing that this is generally a deterioration of the cement and the properties for which we are producing the cement in the first place. Why would we want to ever encourage the carbonation?

Response: We are extremely grateful for your thoughtful review. Carbonization of cement materials does significantly reduce the durability of buildings (Zhang et al., 2025). This paper emphasizes the significance of cement carbon absorption from the perspective of climate change. However, due to misstatements and other reasons, there has been a misunderstanding that we are blindly encouraging carbonation. Therefore, we have revised some of the descriptions. The cement carbon absorption discussed in this study refers to the natural carbonation process of cement, without accelerated carbonation. The focus of the study is to quantify the carbon absorbed in natural carbonation process. While this process contributes to sequestrate CO_2, carbonation of concrete reduces the material's strength and durability. Therefore, from a management perspective, we do not encourage promoting carbonation in concrete service life, except in the case of construction wastes management during the demolition and secondary use stages, which aligns with the management of construction wastes.

Changes: We have deleted the statement in lines 47-48 of the original text.

Line 49: We are a long way from net-zero emissions so long as fossil fuels are used to drive the process.

Response: We sincerely appreciate your insight. In this section, we referenced the cement roadmap to carbon neutrality proposed by cement association in Europe and United States, both of which mention cement carbonation as one of the zero-carbon pathways. This was intended to highlight the importance of accurately quantifying cement carbon uptake. However, the inappropriate phrasing in the original text may have led to the misunderstanding that we advocate for using carbonation as a way to drive the cement industry's net-zero emissions. Therefore, we have made revisions to this part. Thank you for pointing this out, it is of great assistance in enhancing the scientific rigor and clarity of our work.

Changes: We have modified the expression in line 49 of the original text to read: "The cement carbon uptake is helpful to achieve the cement net-zero ambitions for the cement industry". The changes can be found on page 2, line 50 in the revised manuscript.

Line 55: Somewhere in the text it needs to be clear whether this analysis supports or contradicts this 10%. It appears to me that this paper suggests values much larger than 10%.

Lines 363-364: I find this sentence hard to believe. It needs to be very clear. And the contrast with 10% in line 55 should be explicitly stated.

Response: Thanks for your thoughtful comment. The significantly larger of cement CO_2 uptake offsets level in this study (46%) compared to the value (10%) in Portland Cement Association (PCA) of the United States can be attributed to the difference in accounting scope. While the PCA report only includes the carbon sequestration of concrete, our analysis covers a broader range of cement materials, including four types: concrete, mortar, construction waste materials, and cement kiln dust (CKD). In our result, the global carbon uptake from concrete materials accounts for approximately 15.4% of the total emissions from cement production (averaged over the past 100 years), which aligns with the findings in the PCA report. Notably, mortar emerges as the largest contributor to carbon sequestration, accounting for 48% of the total.

Changes: We have emphasized in the manuscript where we introduced the PCA report that he was referring only to concrete materials: "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), …". The changes can be found on page 2, Lines 56-58 in the revised manuscript.

Line 62: I think this should be accuracy rather than precision? Likewise in line 68.

Response: Thank you very much for your suggestion. The optimization of the accounting model in this study is to make the estimation further reflect the true carbon uptake, so using accuracy is a more appropriate word. Your careful review has greatly helped us to improve the quality of our manuscript.

Changes: We have reviewed the entire text and corrected several instances where ‘precise’ was used in place of ‘accurate’, the details are as follows:

Page 1, Line 30: “This study provides an accurate bottom-up quantification to cement carbonation sinks at national and global levels.”

Page 3, Line 64: “Therefore, it is imperative that these uptake estimates are as accurate as possible.”

Page 3, Line 65: “However, due to the lack of detailed activity data and accurate carbonation parameters for various countries, …”

Page 3, Line 70: “…is imperative to collect more accurate activity data on cement consumption with improved spatial resolution.”

Page 4, Line 107: “To provide a more accurate national-level database of carbon uptake in cement, …”

Page 20, Line 406: “… and provide a more accurate bottom-up quantification.”

Line 90: source = sources

Response: Thank you for your suggestion.

Changes: We have changed the source to sources. The change can be found on page 4, line 92 in the revised manuscript.

Line 94: cement clinker data estimated how?

Response: Thank you for pointing this out. Cement clinker consumption data for each country were mainly obtained by multiplying the clinker-to-cement ratio with cement production figures. Cement production data for 163 countries and regions were primarily sourced from the USGS, while clinker-to-cement ratio data for China and India were obtained from statistical data and surveys in prior research (Xi et al., 2016; Guo et al., 2021; Huang et al., 2023). For other countries, cement-to-clinker ratio data were referenced from Andrew's estimates (Andrew, 2020).

Changes: We have changed the description of the cement clinker production data: “Estimated cement clinker consumption data were derived by multiplying clinker-to-cement ratio (the ratio of cement clinker consumption 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).” The changes are reflected on page 4, Lines 96-98 in the revised manuscript.

Line 95: spell out USGS one time and provide the reference.

Response: Thank you for your suggestion.

Changes: We have added the full spelling of USGS and the reference: “Cement production data for 163 countries and regions from 1928 to 2022 obtained from United States Geological Survey (USGS).” The changes are reflected on page 4, Lines 97-98 in the revised manuscript.

Line 98: define “cement clinker ratio”

Response: Thank you for pointing this out. The clinker-to-cement ratio is the ratio of cement clinker production to cement production.

Changes: We have added the define of clinker-to-cement ratio and changed the "cement clinker ratio" to "clinker-to-cement ratio". The changes can be found on lines 96, 103, 133, 199, 209 and 211.

Line 106: source of import - export data.

Response: Thank you for pointing this out. The imported and exported data accessed from UN Comtrade Database. https://comtradeplus.un.org/.

Changes: We have added the source of the import and export data of clinker. The changes are reflected on page 4, Lines 110-111 in the revised manuscript.

Line 107: what is meant by "cement utilization proportion"?

Response: Thank you for pointing this out. The parameters presented here are the proportion of cement used for concrete and mortar in each country. In the accounting model for cement CO_2 uptake, the cement material is categorized into concrete and mortar at the construction service stage (Table 1 in the manuscript), and the estimation for carbon sequestration is constructed according to the respective utilization of these cement materials. Consequently, the amount of cement consumed for each material serves as important activity-level data, determined by multiplying their respective proportion by the total cement consumption.

Changes: We have modified the expression of the parameter here and added the relevant explanation: "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". The changes are reflected on page 4, Lines 112-113 in the revised manuscript.

Line 111: why do we care about "strength class"?

Response: Thank you for your comment. Concrete strength is one of the fundamental performance indicators of concrete and serves as a comprehensive parameter for assessing its quality, which showed large impacts on carbonation rate. It is closely related to the water-cement ratio of the concrete, and it reflects the combined influence of factors on concrete quality such as cement type, cement content, aggregate type, admixtures, as well as construction quality and curing methods. The study shows that concrete with higher strength tends to have greater density, increased resistance to CO_2 diffusion, and a lower carbonation rate. The following table lists the carbonation rates for different concrete strengths, (see in Supplementary Table 2, can be accessed on Zenodo at https://doi.org/10.5281/zenodo.14583866). Therefore, in this study in order to account for the carbon sequestration of cement materials in different countries and regions, we further refined the distribution of concrete strength grades in 42 countries based on the previous study (see in data 2 in Supplementary Table 2)

Table: Concrete carbonation rate coefficients (K) for various concrete strengths and exposure conditions

Region	Exposure condition	Compressive strength (mm/(year)$^{0.5}$)			
Europe (Plain concrete)	k	≤15 MPa	16–20 Mpa	23–35 Mpa	>35MPa
	Exposed outdoor	5	2.5	1.5	1

	Sheltered	10	6	4	2.5
	Indoors	15	9	6	3.5
	Wet	2	1	0.75	0.5
	Buried	3	1.5	1	0.75
China (Plain concrete)	Exposed outdoor	6.1	3.9	2.4	1.3
	Sheltered	9.9	7.1	4.8	2.5
	Indoors	13.9	9.8	7.0	4
	Buried	3.8	1.9	1.0	0.5
	Wet	1.9	1.0	0.7	0.3
USA	uncoated	7.1	6.9	3.8-5.4	2.5
	Coated	n/a	3.5	1.9-2.7	n/a

Changes: We have added reasons for collecting data on concrete grades in different countries: "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."

Line 113: what is CEIC? Spell out once

Response: Thank you for your suggestion. CEIC stands for "China Economic Information Center."

Changes: We have added the full spelling of CEIC: "the concrete categories were estimated based on building types from China Economic Information Center Data (CEIC, 2024)." The changes are reflected on page 4, Line 121 in the revised manuscript.

Line 113: what fraction of cement is used for roads as opposed to buildings?

Response: Thank you for your comment. The utilization of concrete primarily includes construction and infrastructure (such as road and hydraulic engineer). Due to different exposure conditions, particularly variations in CO_2 concentration, the carbonation rates also differ in these projects. In the accounting model for cement CO_2 uptake of this study, both construction and infrastructure are considered as the service stage for concrete. Given data availability, we did not further refine the activity-level data for this stage, such as the fraction of cement for different types of buildings and infrastructure. However, concrete carbonation rate coefficient in the model is adjusted based on environmental factors, according to Eq. 9 in the manuscript:

$$k = \beta_{csec} \times \beta_{ad} \times \beta_{CO_2} \times \beta_{cc} \quad (9)$$

k represents carbonation rates, which is calibrated by exposure conditions (β_{csec}), cement additives (β_{ad}), CO_2 concentration (β_{CO_2}) and coating and cover (β_{cc})

The correction value for CO_2 concentrations in different environments are shown in the following table (see in Supplementary Table 2, which can be accessed on Zenodo at https://doi.org/10.5281/zenodo.14583866). In summary, although the proportion of cementitious materials used in different engineering facilities, such as roads, is not considered, their effect on the carbonation rate is taken into account in the Monte Carlo simulations.

Table: CO_2 concentration and correction value under different environment

Location	CO_2 concentration(ppm)	modified parameter*
Urban	625	1.2
Rual	300	1
Seaside	225	0.93
Industrial area	1200	1.41
Road	1200	1.41
Buried	3000	1

Line 114: "this factor", which factor? Lines 114-118 are not very clear to me.

Response: Thank you for your comment. The factor in here is "Building lifespan". The building lifespan determines the exposure time of concrete during its service phase. In the accounting model for cement CO_2 uptake, we divide the concrete carbon sink into three stages based on principle of life cycle assessment: service, demolition, and secondary-use (including both disposal in a landfill and recycling, with a total lifespan of 100 years in the model. Given the differences in building styles across countries, the varying building lifespans result in differences in concrete exposure duration within the accounting model. Therefore, we collected data on the building lifespan for 42 countries. For the collection of this parameter, we prioritized the use of statistical data and research data (e.g., China), followed by the use of engineering design data and model simulation data instead, such as for Vietnam and India.

Changes: We have changed the introduction in Lines 114-118 of original manuscript: "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)." The changes are reflected on pages 4-5, Lines 121-125 in the revised manuscript.

Line 135: it would be helpful to define carbonation ration and molar ratio

Response: Thank you for your comment. Carbonation ratio is the percentage of carbonation depth (d) compared to the theoretical maximum (D), it varies considerably with the exposure conditions. Molar ratio is the molar mass ratio of CO_2 to CaO (44/56≈0.786).

Changes: We have changed the explanation of calculation methods in Lines 134-139 of original manuscript: "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 annual carbonation ratio, which is the percentage of carbonation depth in accounting year (d) 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 (0.786)." The changes are reflected on page 5, Lines 144-150 in the revised manuscript.

Line 170: CKD could be defined in the table

Response: Thank you for your comment. Cement kiln dust (CKD) is a by-product of cement manufacturing. It is composed of micron-sized particles collected from electrostatic precipitators during the production of cement clinker.(Siddique, 2006). CKD will absorb CO_2 during landfill/waste treatment.

Changes: We have added the cement kiln dust (CKD) in the table 1.

Line 181: USGS defined and reference provided?

Response: Thank you for your comment. USGS is United States Geological Survey, they annually publishes data on cement production in different countries around the world, which can be accessed at https://www.usgs.gov/centers/national-minerals-information-center/cement-statistics-and-information.

Changes: We have added the reference of USGS, and its full spelling has been added in one time. The changes can be found on page 4, lines 98-99 in the revised manuscript.

Line 186: IPCC reference?

Response: Thank you for your comment. Here we cited the 2006 IPCC Guidelines for National Greenhouse Gas Inventories, which can be accessed at https://www.ipcc-nggip.iges.or.jp/public/2006gl/index.html

Changes: We have added the reference of Intergovernmental Panel on Climate Change (IPCC). The changes are reflected on page 4, Lines 106-107 in the revised manuscript.

Line 236: "within the first year" Is this not true for all years?

Response: Thank you for your comment. Here, the author intends to explain that concrete materials cannot be completely carbonized within one year (Qiu, 2020), it leads to a time-lag effect in cement carbon uptake. The depth of carbonation reflects the diffusion range of CO_2 (He et al., 2025). Based on Fick's second law, the carbonation depth of concrete is the product of the carbonation rate factor and the square root of time (You et al., 2022). Studies have shown that the natural carbonation age of concrete ranges from 5 to 60 years (Pan et al., 2016) and that the increase in carbonation depth slows significantly over longer periods of carbonation curing (Qiu, 2020). Therefore, the results of accounting for carbon sequestration in concrete exhibit a time-lag effect, the carbon sequestration of concrete in the current year does not come exclusively from the cement consumed in that year.

Changes: Since the time-lag effect of carbon uptake by cement is in lines 255-259 in the original text, to avoid misunderstandings, we have deleted the original statement and added that explanation to the time-lag effect section: "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." The changes can be found page 12, Lines 281-286 in the revised manuscript.

Line 244: Again, is this not contrary to the reason that one makes cement in the first place?

Response: Thank you very much for your comment. We are sorry that our previous statement created a misconception that carbonization was being encouraged in order to achieve carbon neutrality. Carbonization of cement materials does significantly reduce the durability of buildings (Zhang et al., 2025). From a management perspective, we advocate enhanced carbonization of cement materials at the waste disposal and recycling stages, such as waste concrete (Mo and Panesar, 2013), and CKD (Pu et al., 2023).

Changes: In order to avoid misunderstandings in the presentation, we have changed the presentation in the section 3.1: "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." The changes can be found page 11, Lines 258-264 in the revised manuscript.

Text beginning on line 246: use of the term "historical year" is not very clear. Does this refer to each historical year? Line 249: again, is this referring to each historical year?

Response: Thank you very much for your comment. As an example, for the total carbon uptake from cement in 2023, the current-year uptake is the carbon sequestration resulting from the carbonization of the cement consumed in 2023, and the historical-year uptake is the carbon sequestration in 2023 due to the incomplete carbonization of the cement consumed before 2023.

Changes: We changed the interpretation of historical-year uptake: "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." The changes can be found page 12, Lines 273-274 in the revised manuscript.

Line 252: Does this really say that most C uptake takes place within current year production?

Response: Thank you very much for your comment. Your observations are correct. The carbonation rate of concrete materials during the building service phase decreases gradually, and although they cannot be fully carbonized in one year, most of the carbonation occurs in the first year of service. Therefore, carbon uptake in the current year is predominant. Additionally, the gradual increase in the share of carbon uptake in historical years is a result of accumulation.

Changes: we have added Figure 2 to improve the clarity and readability of this section:

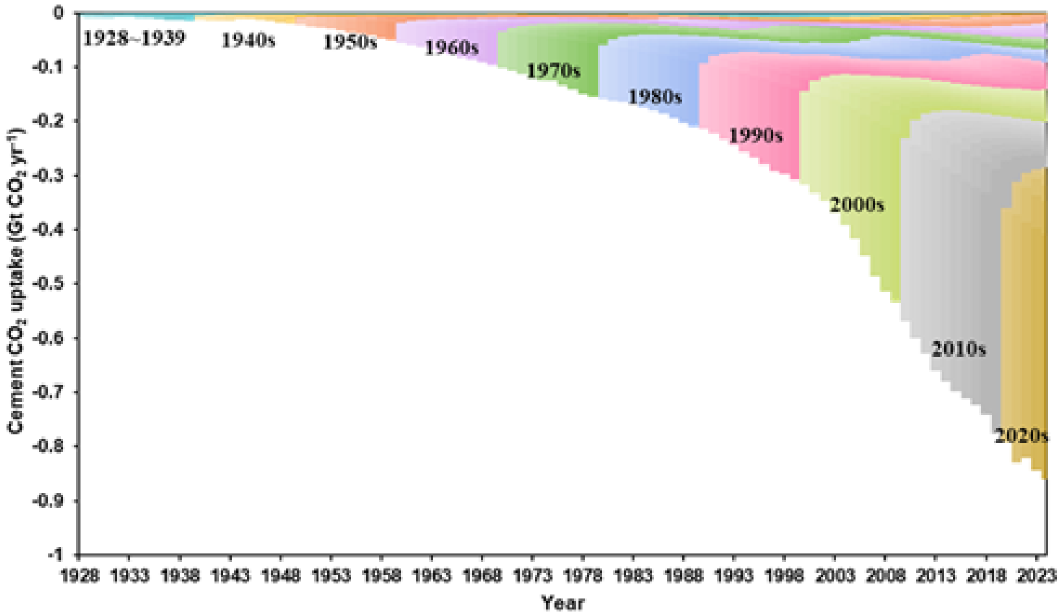

Figure 2: Time-lag effect on carbon uptake by cement from 1928 to 2024. Different colours represent changes in carbon sequestration over time for different years of consumption of cement.

Lines 305-306: Here it is important to distinguish clearly between emissions and net emissions.

Response: We are grateful for your review. The emissions for the cement industry include both fossil fuel emissions and chemical process emissions. Therefore, the emissions in this study refer to process emissions, and the net emissions reflect process emissions after deducting of cement carbon sequestration. We have added it at the application of line 47 of the original text.

Changes: We have added the definition of "net emission": "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 (namely industrial process of cement production minus the CO_2 sequestration from carbonation of cement materials) were only about 57% of the cumulative process emissions from 1930 to 2013 (Xi et al., 2016)." The changes can be found page 2, Lines 46-49 in the revised manuscript.

Many of these points may seem like nit picking of minor issues, but collectively they are very important to a clear understanding of what was done in this paper and how we should treat the results. I encourage complete and comprehensive discussion of data sources and computations.

Response: We are very appreciated of your meticulous review. Your comprehensive comments and suggestions have not only contributed to improve the quality of this manuscript but also broadened our perspective on this research topic.

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