Supplementary Information for:

A framework for integrating cement carbonation sink into national greenhouse gas inventories

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Content

Supplementary Note 1: Countries covered in this study

This study focuses on major cement consumption countries and the Annex I countries defined under UNFCCC. There are 14 major cement consumption countries for which cement production data are recorded annually by the United States Geological Survey (USGS)[1], including the United States of America, Brazil, China, Egypt, India, Indonesia, Iran, Japan, South Korea, Mexico, Russia, Saudi Arabia, Turkey, and Vietnam. The Annex I countries comprise 44 parties, and they are required to submit their national GHGs inventory reports in common reporting format tables every year, with consistent and high-quality time-series cement process emissions data. Among the 44 Annex I parties, the European Union is not a sovereign state and does not report cement-related data as a separate entity, Monaco's emissions have been combined with those of France, and Malta and Liechtenstein do not have domestic cement producer, so these four parties were excluded. Therefore, the final dataset comprises 50 countries in this study, the other 36 countries are: Australia, Austria, Belarus, Belgium, Bulgaria, Canada, Croatia, Cyprus, Czechia, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Kazakhstan, Latvia, Lithuania, Luxembourg, Netherlands, New Zealand, Norway, Poland, Portugal, Romania, Slovakia, , Slovenia, Spain, Sweden, Switzerland, Turkey, Ukraine, and the United Kingdom. As shown in the Figure S1, the 50 countries coverage in this study account for 88% global cement consumption.

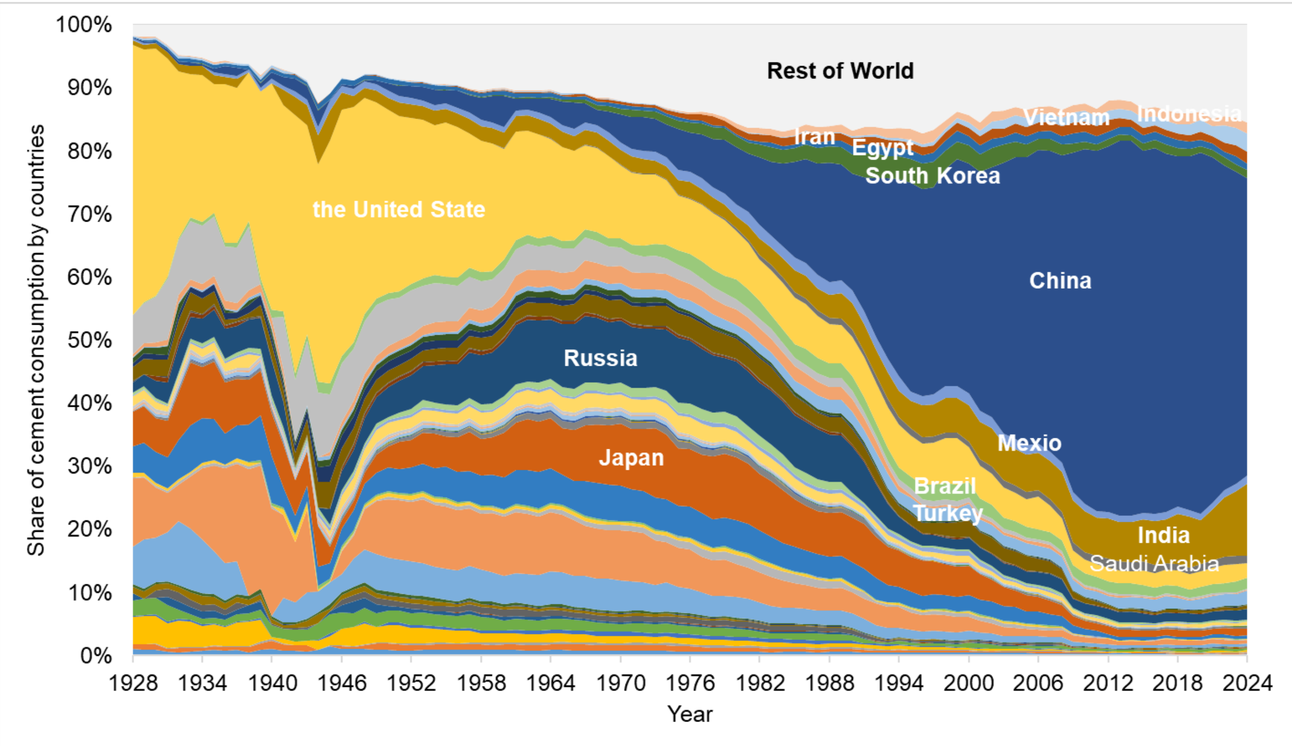

Fig. S1: Share of cement consumption by 50 countries. The map highlights 14 major consumer countries (77% global cement consumption). Detailed data see in Source Data.

Supplementary Note 2: The activity data in the Tier 1 and Tier 2 method

In the cement production stage, clinker production in reporting year is the activity data, the data should prioritize official statistics or industry associations. If clinker production data is unavailable, it can be calculated using the cement clinker ratio relative to cement production as following:

$$P_{clinker,y} = P_{cement,y} \times CKR_y$$

Where $P_{clinker,y}$ is clinker production in reporting year y, $P_{cement,y}$ is the cement production in reporting year *y*, CKR_y is the clinker-to-cement ratios in year *y*, which defined as the mass ratio of clinker consumption to cement production.

In the cement service life, demolition, and disposal stages, the activity data is the time-series of cement consumption (c_1, ··· c_j, ··· c_y), corrected by clinker fraction:

$$AD = C_{cement} \times F_{clinker}$$

AD is the activity data, C_{cement} is the cement consumption, $F_{clinker}$ is the clinker fraction in cement materials.

Cement consumption can be can be estimated based on the cement production and trade data as following:

$$C_{cement,y} = P_{cement,y} + Im_{cement,y} - Ex_{cement,y}$$

Where $C_{cement,y}$ is the cement consumption in reporting year y, $P_{cement,y}$ is the cement production in year y, $Im_{cement,y}$ and $Ex_{cement,y}$ are the imports and exports of cement in year y.

$F_{clinker}$ is suggested to adopt a global default value of 0.95[2,3]. If $F_{clinker}$ is not statistically analyzed, it can be can be replaced by the clinker-to-cement ratios. We employed linear interpolation[3] to reconstruct historical clinker-to-cement ratios.

The source of activity data in 50 countries can be obtained in source data, and the activity data are in Supplementary Table1.

Supplementary Note 3: Global default absorption factors of cement carbonation in the Tier 1 method

3.1 Global default carbon absorption factors in Tier 1A.

In the Tier 1 method, the global average absorption factors of cement carbonation (Fig. S2) were used as default absorption factors. It is derived from the weighted average of cement carbon absorption factors across 50 countries with the weights determined by cement consumption.

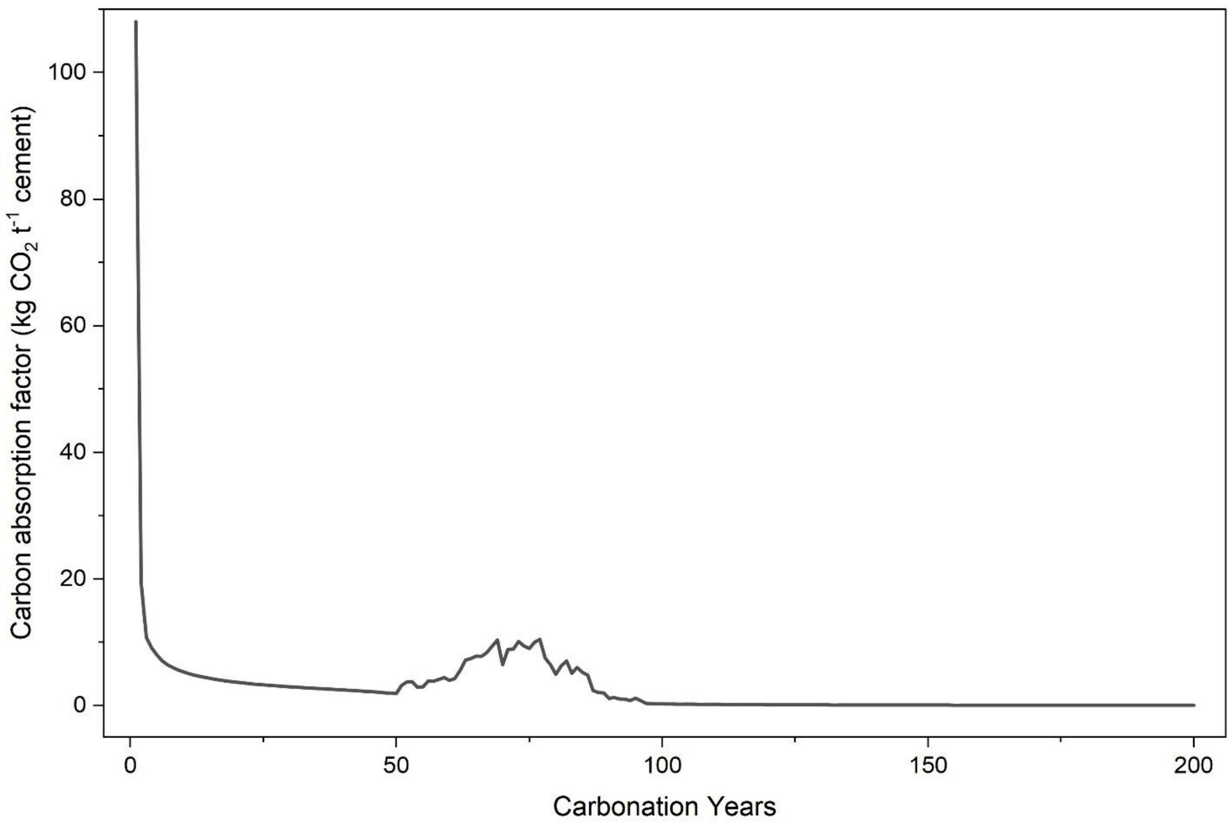

Fig. S2: Global default carbon absorption factor curves.

3.2 Global default carbon absorption factors in Tier 1B.

Principal component analysis (PCA) was applied to the five key parameters comprising 18 variables to explore the dominant structural differences among 50 countries. The analysis indicates that the parameter space can be effectively represented by two principal components, which explain 43.3% and 28.6% of the total variance, respectively. Together, the first two principal components account for 71.9% of the total variance, capturing the dominant inter-country differences. Higher-order components each explain less than 10% of the variance and were therefore not considered in the main analysis.

The principal component loading matrix is presented in Table S1. The first principal component (PC1) is characterized by high positive loadings on the four particle-size distributions associated with RCA for new cement concrete, as well as on building lifespan, the third concrete strength class, and the proportion of cement used for concrete. In contrast, the particle-size distributions associated with landfill and stacking exhibit strong negative loadings on PC1. This component therefore represents a gradient from landfill-dominated disposal pathways toward intensive recycling into new cement concrete combined with longer building lifespans and higher concrete use intensity. The second principal component (PC2) shows high positive loadings on the particle-size distributions related to RCA for road base materials, while the particle-size distributions associated with landfill and stacking remain negatively loaded. PC2 thus captures the differentiation between road-base-oriented recycling pathways and landfilling practices.

Table S1. Principal component loading matrix

Carbonation parameters		**Variables**	**PC1**	**PC2**
Proportion of cement used for concrete		Cement_share	0.207183	0.049206
Distribution of concrete strength class	<C15	strength_1	-0.09287	-0.13692
	C16-C23	strength_2	-0.34776	-0.01134
	C24-C35	strength_3	0.501042	0.134247
	>C35	strength_4	-0.22113	-0.13134
Building lifespan		lifespan	0.696594	-0.1729
RCA for new cement concrete	<5mm	d1_g1	0.996141	-0.0778
	5-10mm	d1_g2	0.980302	-0.06474
	10-20mm	d1_g3	0.99974	-0.07341
	20-32mm	d1_g4	0.999272	-0.07274
RCA for Road base materials and others	<1mm	d2_g1	-0.32822	0.930131
	1-10mm	d2_g2	-0.36628	0.938027
	10-30mm	d2_g3	-0.37677	0.934331
	>30mm	d2_g4	-0.37974	0.93257
Landfill and Stacking	<10mm	d3_g1	-0.75776	-0.6603
	10-30mm	d3_g2	-0.75763	-0.66044
	30-50mm	d3_g3	-0.75777	-0.66028
	>50mm	d3_g4	-0.75772	-0.66035

Based on the principal component scores of the 50 countries, hierarchical clustering was first performed to explore the grouping structure. The dendrogram and agglomeration schedule suggest the presence of three distinct clusters (Fig. S3). To further validate the robustness of the clustering solution, K-means clustering was applied to the same principal component scores, and the results consistently indicate that three clusters provide the optimal partition of the countries (Fig. S4).

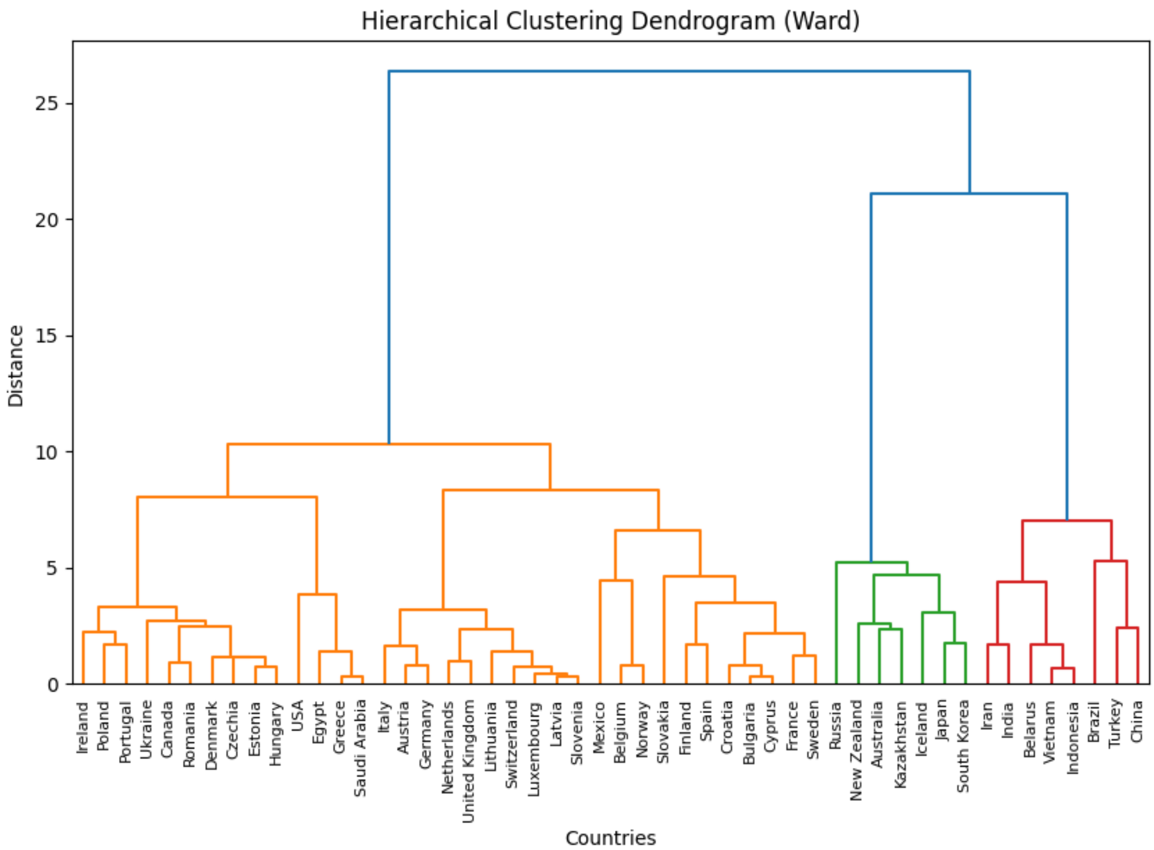

Fig. S3: Hierarchical clustering dendrogram.

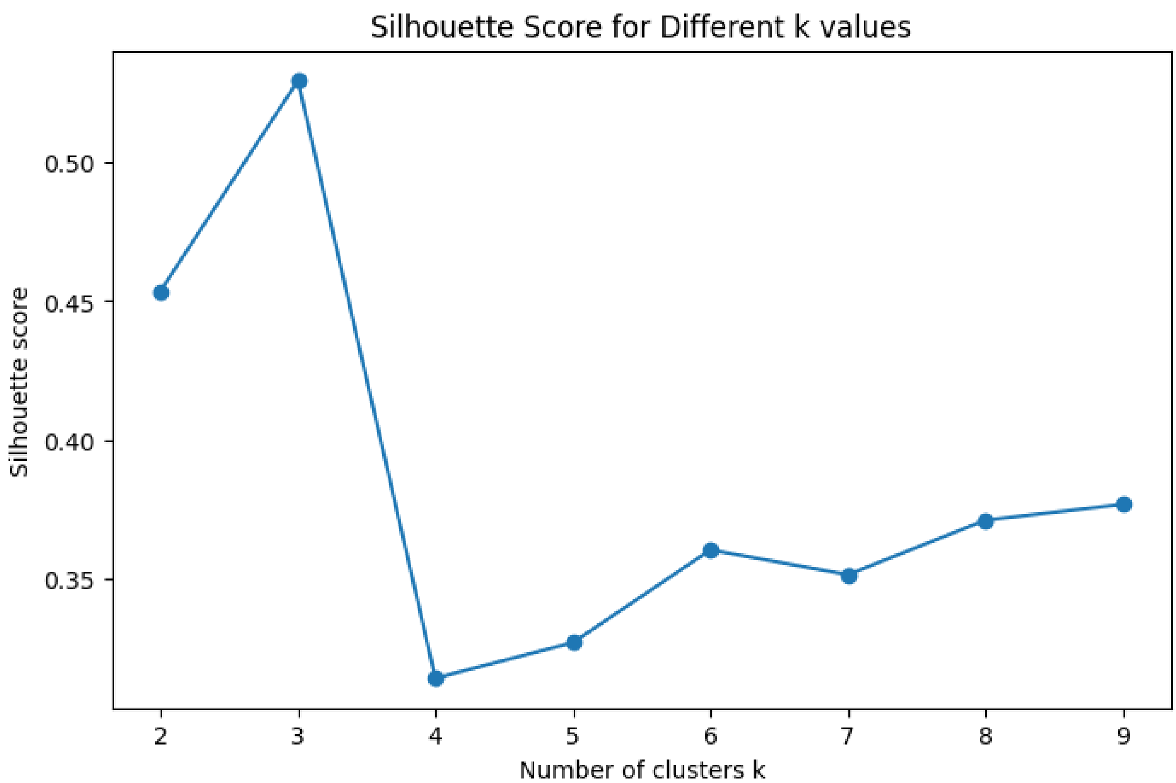

Fig. S4: Silhouette coefficients for K-means clustering results at each k value.

On this basis, the 50 countries were classified into three distinct groups (Fig. S5).

Group I, characterized by high PC1 scores, consists mainly of Europe and other industrialized regions, including Austria, Germany, France, the United Kingdom, the United States, and Canada, as well as several emerging economies such as Mexico, Egypt, and Saudi Arabia. These countries are dominated by recycling of waste concrete into new cement concrete (67.57%), generally exhibit finer particle-size distributions (mainly 11-20mm), longer building lifespans, and higher proportions of cement used for concrete.

Group II is characterized by low scores on both PC1 and PC2 and mainly includes developing countries such as China and India. In these countries, waste concrete is predominantly disposed of through landfill and stacking (93.19%), with coarser particle sizes (mainly >50mm), shorter building lifespans (50 years), and relatively lower proportions of cement used for concrete (67.85%).

Group III exhibits relatively low PC1 scores but high PC2 scores, indicating a disposal structure dominated by the use of waste concrete as road base materials (71.54%). These countries are generally associated with shorter building lifespans (45 years) and a concrete strength distribution concentrated in the C16-C23 strength class (42.69%).

Table S2. The countries included in the three categories

	Group 1	**Group 2**	**Group 3**
Number of countries	35	8	7
Countries	Austria, Belgium, Bulgaria, Canada, Croatia, Cyprus, Czechia, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Netherlands, Norway, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden, Switzerland, Ukraine, the United Kingdom, the United State, Mexico, Egypt, Saudi Arabia	Belarus, Turkey, Brazil, Iran, India, China, Vietnam, Indonesia	Australia, Iceland, Japan, Kazakhstan, New Zealand, Russia, South Korea

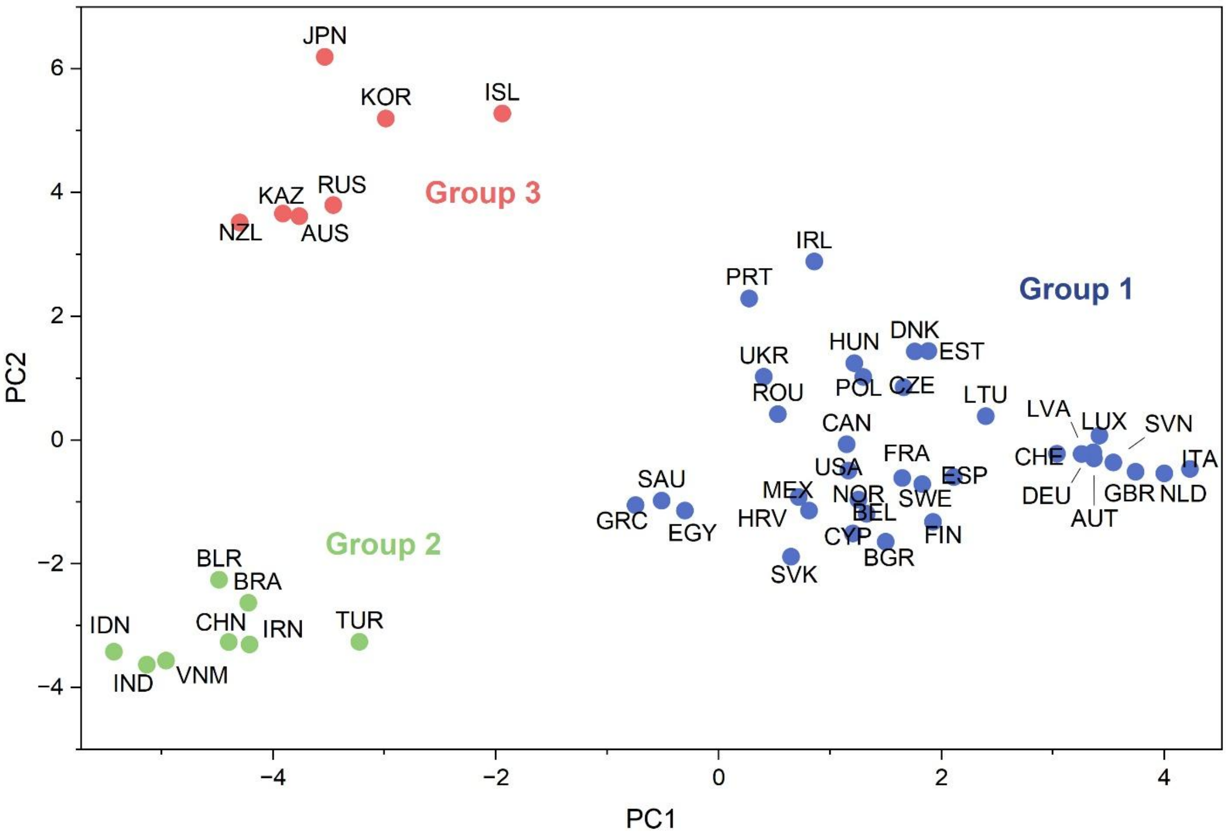

Fig. S5: PCA score plot of countries based on the first two principal components (PC1 and PC2).

The ranges of the five key parameters for the three clusters are summarized in Table S3. Countries may identify their corresponding cluster by comparing national parameter values with these ranges, thereby selecting the appropriate Tier 1B default carbon absorption factors.

Table S3. The ranges of the five key carbonation parameters for the three groups.

Carbonation parameters		Group 1	Group 2	Group 3
Proportion of cement used for concrete		74.00% (49.74%-95.69%)	67.85% (55.01%-80.60%)	71.78% (40.90%-86.11%)
Distribution of concrete strength class	<C15	6.76% (0.03%-31.25%)	8.06% (1.50%-16.50%)	5.6% (0.33%-9.40%)
	C16-C23	35.99% (4.20%-77.00%)	45.20% (13.70%-83.12%)	42.69% (23.18%-65.80%)
	C24-C35	45.06% (11.33%-78.64%)	28.22% (2.09%-66.00%)	39.1% (15.48%-54.55%)
	>C35	13.82% (2.00%-47.34%)	19.51% (2.92%-47.34%)	14.3% (9.32%-23.48%)
Building lifespan		67 (35-100)	50 (40-100)	45 (13-90)
Distribution in different disposal types	RCA for new cement concrete	67.57% (41.20%-99.80%)	3.09% (0.00%-9.50%)	8.30% (2.00%-19.90%)
	RCA for Road base materials and others	13.88% (0.00%-48.10%)	3.79% (0.00%-12.50%)	71.64% (65.00%-88.50%)
	Landfill and Stacking	18.55% (0.20%-44.90%)	93.19% (83.30%-99.50%)	20.07% (4.70%-32.00%)
RCA for new cement concrete	<5mm	28.99% (14.90%-29.40%)	20.34% (14.90%-29.40%)	21.11% (14.90%-29.40%)
	5-10mm	14.12% (13.80%-25.10%	20.86% (13.80%-25.10%)	20.26% (13.80%-25.10%)
	10-20mm	39.24% (39.20%-40.60%)	40.08% (39.20%-40.60%)	40.00% (39.20%-40.60%)
	20-32mm	17.65% (17.60%-19.40%)	18.73% (17.60%-19.40%)	18.63% (17.60%-19.40%)
RCA for Road base materials and others	<1mm	15.59% (11.70%-15.70%	13.20% (11.70%-15.70%)	13.41% (11.70%-15.70%)
	1-10mm	27.48% (26.90%-27.50%)	27.13% (26.90%-27.50%)	27.16% (26.90%-27.50%)
	10-30mm	39.28% (39.20%-42.00%)	40.95% (39.20%-42.00%)	40.80% (39.20%-42.00%)
	>30mm	17.65% (17.60%-19.40%)	18.73% (17.60%-19.40%)	18.63% (17.60%-19.40%)
Landfill and Stacking	<10mm	17.80% (12.20%-25.60%)	17.80% (12.20%-25.60%)	17.80% (12.20%-25.60%)
	10-30mm	27.10% (19.50%-35.40%)	27.10% (19.50%-35.40%)	27.10% (19.50%-35.40%)
	30-50mm	17.30% (10.60%-22.50%)	17.30% (10.60%-22.50%)	17.30% (10.60%-22.50%)
	>50mm	37.80% (24.80%-48.40%)	37.80% (24.80%-48.40%)	37.80% (24.80%-48.40%)

Supplementary Note 4: The parameters for national absorption factors of cement carbonation in the Tier 2 method.

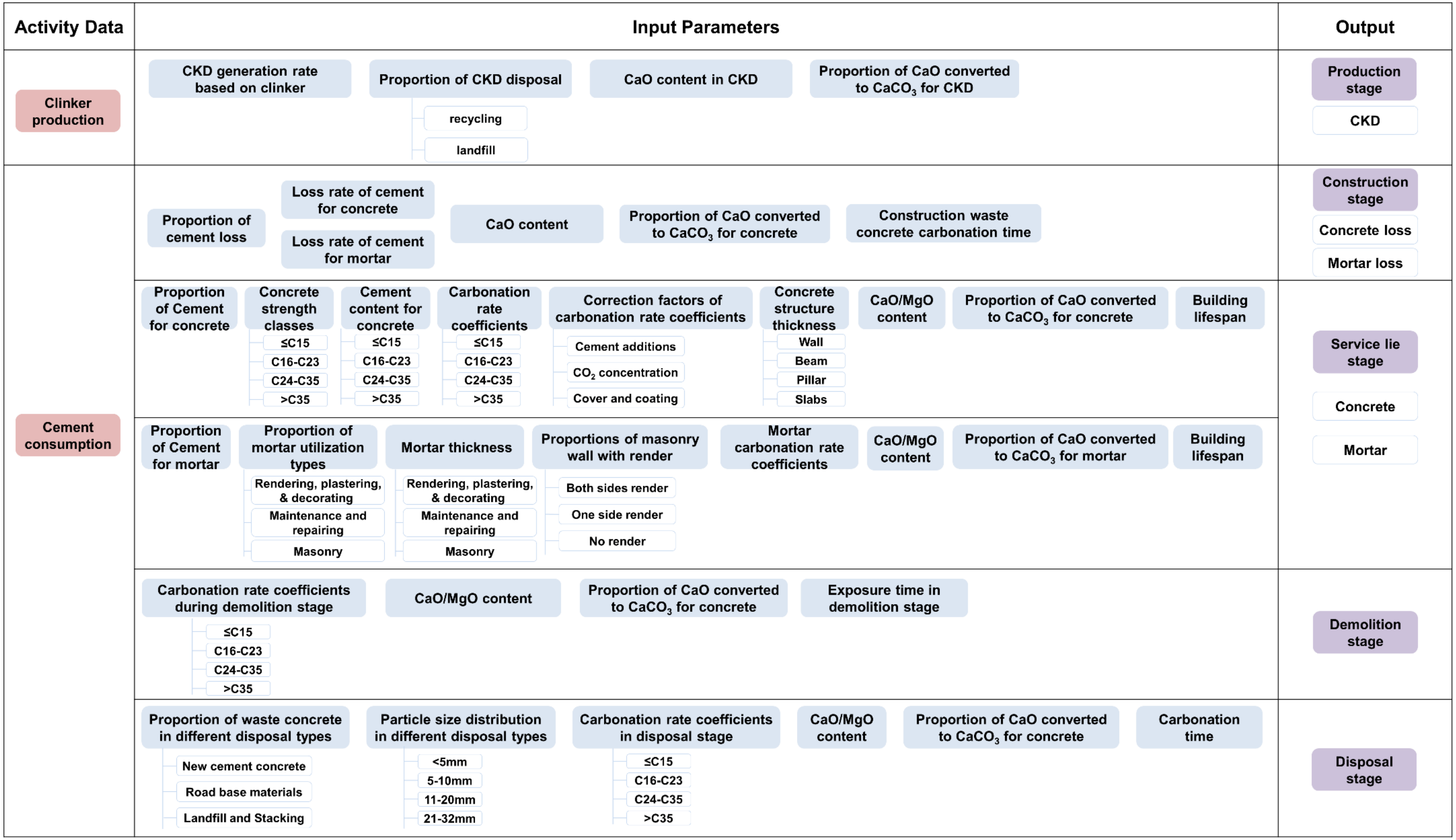

Fig. S6: Input parameters for national absorption factors of cement carbonation in the Tier 2 method

4.1 Global Parameters

The CaO and MgO contents in cement materials, as well as the proportion of CaO (MgO) converted to $CaCO_3$ ($MgCO_3$), are required input parameters for calculating cement absorption factors at all life-cycle stages. They are considered as global parameters.

4.1.1 CaO/MgO content in cement

CaO and MgO are the principal components governing the carbonation potential of cement-based materials, and their abundance determines the theoretical maximum extent of carbonation. Although CKD is generated as dust during cement production, its chemical composition differs substantially from that of clinker. Accordingly, we calculate the absorption factors for the production and consumption stages using the CaO/MgO contents of CKD and clinker as input parameters, respectively. Previous study[4] indicates that CKD typically contains about 44.10% CaO (range: 19.0%–61.23%) and less than 1% MgO. In contrast, clinker has an average CaO content of 65.0% (60.0%–67.0%)[5] and an average MgO content of approximately 2.5% (0–5.0%)[6,7]. We vary the CaO/MgO contents of both CKD and clinker using a triangular distribution, see Data 1.3 and Data 3.4.4 for details in Supplementary Table2.

4.1.2 Proportion of CaO converted to $CaCO_3$

The degree to which CaO is converted to $CaCO_3$ during carbonation is another global parameter that directly determines the actual uptake of CO_2. This ratio reflects the fraction of reactive CaO that ultimately participates in carbonation under realistic environmental or operational conditions. Given the variability in reaction kinetics and exposure environments, we treat proportion of CaO converted to $CaCO_3$ as an uncertain parameter and assign it a Weibull distribution in the Monte Carlo analysis. Based on multiple experimental studies[8-11], the conversion ratio of CaO to $CaCO_3$ in concrete ranges from 50% to 90%. The shape and scale parameter of the Weibull distribution were set to 25 and 86.0%, respectively (see Data 3.4.5 for details in Supplementary Table2). The proportion of CaO to $CaCO_3$ in mortar is range from 50.2% to 100%, which is from experimental tests in our previous study[12]. The shape and scale parameter of the Weibull distribution were set to 20 and 91.45%, respectively (see Data 3.5.2 for details in Supplementary Table2).

4.2 Local parameters

4.2.1 Input parameters in cement production stage

Cement kiln dust (CKD) is an intrinsic process residue generated during cement production[4]. A part of CKD can be recycled to clinker production, while the rest is considered to be "lost" to the process. This lost CKD is not ultimately deployed in cement products, but its exposure to the atmosphere in disposal sites or other applications enables carbonation. Therefore, the associated carbon absorption should be included in the sink inventory. The particles of CKD are extremely fine (<200μm), its substantial carbonization within the first two days of landfill reaction and completing full carbonization within one year. Consequently, the carbon absorption factor for CKD in the inventory is specific to the reporting year. It is dependent on parameters of the annual CKD generation rate and proportion of CKD to landfill etc.

4.2.1.1 CKD generation rate based on clinker

CKD generation rates vary dramatically among facilities in cement industry. Clinker production as the activity data for carbon sequestration accounting during the production phase, which is consistent with the activity data for emissions from production activities. Accordingly, this parameter represents the ratio of CKD output to clinker production. For national-scale assessments, it is recommended that countries derive this ratio from annual plant-level statistics. In this study, the CKD generation rate is set at 6.0% (range: 4.1%–11.5%)[4] and modeled using a triangular distribution, see Data 1.1 in Supplementary Table2.

4.2.1.2 Proportion of CKD to landfill

Previous studies[4,13] reported that that approximately 80% (range: 52%–90%) of CKD removed from cement kilns is disposed of in landfills, while the remaining 20% portion is beneficially reused. This parameter is modeled using a triangular distribution to capture its variability, see Data 1.2 in Supplementary Table2. As technological advancements improve CKD recycling and reuse pathways, the landfill share may change over time. It is therefore recommended that facilities track this parameter annually to reflect evolving CKD management practices.

4.2.2 Input parameters in construction stage

During the construction phase, some concrete and mortar are lost and subsequently backfilled and buried[14-15] to undergo carbonation reactions. The input parameters for the cement carbon absorption factor at this stage primarily include proportion of cement loss, the loss rate for concrete and mortar, and carbonation time, see Data 2 in Supplementary Table2.

4.2.2.1 Proportion of cement loss in construction processing stage

It refers to the proportion of losses during the construction period relative to total cement consumption. Construction budget standards[16] and previous study[17] indicate that between 1 and 3% of cement is lost during construction. We therefore vary the parameter assuming a triangular distribution spanning this range and with a mode value of 1.5%.

4.2.2.2 Loss rate of cement for concrete/mortar

It refers to the ratio of concrete/mortar in cement loss. For concrete, the cement loss rate is modeled using a triangular distribution with a mode of 41.4% and a range of 20%–60%. For mortar, the loss rate is likewise modeled as a triangular distribution, with a mode of 58.6% and a range of 40%–80%.

4.2.2.3 Construction waste concrete carbonation time

Most construction waste is in the form of small particles[14], the construction loss mortar can be fully carbonized within one year. The construction waste concrete carbonation time is estimated in triangular distribution with mode value is 5 years, maximum value is 10 years, and minimum value is 1 year.

4.2.3 Input parameters in service life stage

During the service life, the differences in material properties and exposure conditions between concrete and mortar necessitate distinct approaches for calculating their carbonation factors.

4.2.3.1 Input parameters in service life stage for concrete

The input parameters for concrete carbonation including the proportion of cement for concrete, concrete strength classes distribution, cement content in concrete, and carbonation rate coefficients in different strength classes, correct factor of carbonation rate coefficients by environment, and the concrete structure thickness.

(1) Proportion of cement for concrete

It represents the proportion of cement consumption for concrete and is modeled using a Weibull distribution. Data for European countries were collected from the European Ready Mixed Concrete Organization (EMRCO)[18]. Data of the United State were derived from United States Geological Survey (USGS) statistics[1], the scale parameter is 85.98% and the shape parameter is 4, with a range of 68.94%-89.41%. Chinese data were sourced from industry surveys[12], the scale parameter is 69.34% and the shape parameter is 4, with a range of 67.07%-71.16%. For Brazil and Mexico[19], the scale parameter is 60.00% and the shape parameter is 4, with a range of 55.00%-65.00%. For Egypt[20], the scale parameter is 82.22% and the shape parameter is 4, with a range of 63.00%-93.33%. For Indian[21], the scale parameter is 80.06% and the shape parameter is 4, with a range of 28.85%-88.31%. For Indonesia and Vietnam[22], the scale parameter is 66.11% and the shape parameter is 4, with a range of 50.86%-90.22%.

The proportion of cement used in concrete is critical for calculating the carbon absorption factor of cement, with sensitivity around 70%[12]. However, this value currently lacks official statistics.

(2) Concrete strength classes distribution

It refers to the proportion of concrete distributed in different strength classes: less than 15 MPa (<C15), between 16 MPa and 23 MPa (C16–C23), between 24 MPa and 35 MPa (C25–C35), and greater than 35 MPa (>C35), and it is modeled using a Weibull distribution. This parameter varies largely across countries. We collected data for European countries from ERMCO[18] and estimated the values for other countries based on national building-type data from China Economic Information Center Data (CEIC)[21]. See Data 3.2 in Supplementary Table2.

(3) Cement content in concrete

It refers to the cement content in different concrete strength classes. For each class, the cement content is varied using a uniform distribution. The minimum and maximum values are 165–288 kg/m^3 for strength class <C15, 240–390 kg/m^3 for C16–C23, 280–400 kg/m^3 for C25–C35, and 300–670 kg/m^3 for >C35.

(4) Carbonation rate coefficients

It refers to the carbonation coefficients in different concrete strength classes. The methodology in this study is based on the most widely used empirical carbonation model, which is that the carbonation depth is proportional to the square root of the carbonation time[24]. This model considers only one independent variable, while other factors are considered in a carbonation coefficient "k". The previous literatures[10,25-28] suggested the carbonation rate coefficients by categorizing the concrete based on strength and exposure conditions. Concrete carbonation coefficients in China are derived from more than 1300 concrete samples all over the China[12]. For each concrete strength class, the carbonation rate coefficients are modeled using uniform distribution, see Data 3.4.2 in Supplementary Table2.

Table S4. Carbonation rate coefficients (k) for various concrete strengths and exposure conditions in Europe[23].

Exposure condition	Compressive strength (mm/(year)0.5)			
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

Table S5. Carbonation rate coefficients (k) for various concrete strengths and exposure conditions in China[9].

Exposure condition	Compressive strength (mm/(year)0.5)			
K	≤15 MPa	16–20 Mpa	23–35 Mpa	>35MPa
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

(5) Correction factor of carbonation rate coefficients

Cement additives can increase the carbonation rate of cement materials[9,29-31]. Elevated CO_2 concentrations in industrial environments[32] and near roadways can further accelerate carbonation rate[33-35]. Conversely, the application of surface treatments reduces carbonation, such as paints or protective coatings[36]. Studies have shown that coating layers can reduce carbonation rates by 0–50%[10,35-39]. In the model, the three correction parameters are represented using Weibull distributions, respectively. For the correction factor of cement additions, the minimum and maximum bounds are set to 1.0 and 1.3, respectively, with shape and scale parameters of 20 and 1.16. The same bounds and Weibull parameters (minimum 0.93, maximum 1.2, shape 20, scale 1.18) are applied to the correction factor of CO_2 concentration. Similarly, the correction factor of cover and coating protection also uses a Weibull distribution with minimum 0.50, maximum 1.0, and shape and scale parameters of 6 and 1.0. See Data 3.4.3 in Supplementary Table2. The correction factor of cover and coating is applied only to the service life stage and not considered during its demolition stage.

(6) Concrete structure thickness

It refers to the wall thickness of various building structures. Wall and structure thicknesses worldwide range from 60 to 610 mm, with most between 100 and 490 mm[40-43]. It is modeled as a Triangular distribution with mode value 250 mm, and a range of 100-490 mm, see Data 3.4.6 in Supplementary Table2.

(7) Building lifespan

Consistent with prior research[44-46], building lifespan parameters are represented using a Weibull distribution. The scale and shape parameters see Data 3.3 in Supplementary Table2.

Table S6. Building lifespan range in different countries and regions.

Countries and regions	Building lifespan	References
China	42 (4~73)	12
Europe	75 (50~90)	47,48
USA	74.1 (56.9~82.4)	44
Brazil	75 (50~100)	49
Africa	45 (40~50)	50
Japan	27 (25~30)	51,52
South Korea	21 (13~30)	53
Indonesia	23 (10~35)	54
India	50 (35~70)	55-60

4.2.3.2 Input parameters in service life stage for mortar

The input parameters for mortar carbonation factor including the proportion of cement for mortar, proportion of mortar utilization types, mortar thickness in three utilization types, proportions of masonry wall with render, and mortar carbonation rate coefficient.

(1) Proportion of cement to mortar

It refers to the proportion of cement consumed in mortar, and it can be calculated as the complement of concrete utilization, i.e., 1 minus the concrete proportion.

(2) Proportion of mortar utilization types

Mortar is predominantly used in three application categories: (1) rendering, plastering and decorating, (2) masonry, and (3) maintenance and repairing[61]. The majority of mortar is consumed in rendering, plastering, and decorating[62]. The parameter is modeled using a Weibull distribution with a scale of 52.4% and a shape of 14, spanning a range of 24.0%–72.5%. For masonry, the Weibull distribution uses a scale of 18.8% and a shape of 12, with values ranging from 1.7% to 52.2%[12]. The maintenance and repairing mortar's proportion is obtained as one minus the proportions of the aforementioned two.

(3) Proportions of masonry wall with render

This parameter represents the proportion of masonry mortar used in three wall configurations: (1) both sides rendered, (2) one side rendered, and (3) no rendering. According to our previous survey projects[12], we vary the shares of masonry walls with different rendering extents using triangular distributions: a mode of 60% (range: 40%–90%) for walls rendered on both sides; a mode of 30% (range: 10%–50%) for walls rendered on one side; and a mode of 10% (range: 0%–20%) for walls without rendering. These parameter ranges are assumed to be applicable globally.

(4) Mortar thickness

It refers to the thickness of mortar in three mortar utilization types. Mortar is typically applied in relatively thin layers with large exposed surface areas[61]. Mortar thickness exerts a notable influence on carbonation potential. The thickness of mortar used for rendering, plastering, and decorating is modeled using a Weibull distribution with a scale parameter of 22 mm and a shape parameter of 4, within a range of 3–50 mm. For masonry mortar, thickness is also represented by a Weibull distribution with a scale of 11 mm and a shape of 8, ranging from 5–20 mm. For maintenance and repair applications, mortar thickness follows a Weibull distribution with a scale of 26.8 mm and a shape of 7, spanning a range of 10–50 mm[43,62].

(5) Mortar carbonation rate coefficient

The mortar carbonation rate coefficient during the demolition stage was determined in our previous experiment study[12] (see Table S4). This parameter is modeled as a Triangular distribution with a mode 19.6 mm/year$^{0.5}$ and range from 6.1 to 36.8 mm/year$^{0.5}$.

Table S7. Mortar carbonation rate coefficients measured in China[12]

Cement types	Strength class	Exposure conditions	Average (mm/year$^{0.5}$)	Max (mm/year$^{0.5}$)	Min (mm/year$^{0.5}$)
Portland cement	M15	Outdoor	11.1	22.1	4.2
		Indoor	25.5	36.5	15.4
	M20	Outdoor	10.4	19.2	4.3
		Indoor	23.9	36.5	13.9
	M25	Outdoor	10.5	17.9	5.2
		Indoor	23.9	37.8	15.2

	M30	Outdoor	10.8	21.6	4.8
		Indoor	23.5	32.5	16.3
Fly ash cement or slag cement	M15	Outdoor	13.6	19.9	7.1
		Indoor	29.1	35.4	23.3
	M20	Outdoor	14.2	21.2	7.1
		Indoor	29.9	37.1	22.3
	M25	Outdoor	14.3	20.8	9.0
		Indoor	28.8	38.8	20.8
	M30	Outdoor	13.4	21.6	7.1
		Indoor	30.2	39.4	22.6
Average			19.6	36.8	6.1

4.2.4 Input parameters in demolition stage

In demolition stage, the input parameters include carbonation rate coefficient and exposure time.

(1) Carbonation rate coefficient in demolition stage

This refers to the carbonation rate of concrete in the demolition stage, evaluated as the service-phase carbonation rate after removing the correction factor associated with cover and coating protection.

(2) Exposure time in demolition stage

This parameter represents the duration of cement exposure during the building demolition phase, measured in years. It is modeled using a Weibull distribution, with a shape parameter of 4 and a scale parameter of 0.4 years, and bounded by a minimum of 0.1 years and a maximum of 1.0 year[63].

4.2.5 Input parameters in disposal stage

During the disposal phase, demolished concrete is crushed into fine particles and processed through different disposal ways. The parameters considered in this stage include: proportion of waste concrete in different disposal ways, particle size distribution in different disposal ways, carbonation rate coefficients in disposal stage, and carbonation time.

(1) Proportion of waste concrete in different disposal ways

It represents the proportion of different disposal ways for waste concrete. We consider three primary end-of-life pathways for demolished concrete: Recycled Concrete Aggregates (RCA) for new cement concrete (direct recycling into concrete), RCA for Road base materials and others (use as road-base / sub-base and other civil-engineering fill applications), and landfill and stacking. The parameters are modeled using a Triangular distribution, see Data 5.1 in Supplementary Table2.

In countries with advanced waste management systems, this parameter is recorded by specialized statistical agencies. For example, Japan's Ministry of Land, Infrastructure, Transport and Tourism (MILT)[64] and the United States Environmental Protection Agency (EPA)[65] provide survey data on waste concrete. Eurostat[66] compiles detailed annual data on various disposal methods for both hazardous and non-hazardous construction waste across EU member states. In contrast, in most developing countries, demolished waste remains poorly managed due to limitations in legislation, public awareness, and technological capacity. For instance, demolished waste is not included in China's environmental statistical yearbook, and the reuse rate of demolition materials in India and Vietnam is below 1% with no standardized statistical tracking. Therefore, the input parameter settings for these countries are primarily derived from literature sources. However, demolished waste management and statistics are crucial for obtaining cement carbon absorption factors.

(2) Particle size distribution in different disposal ways

It refers to the particle size of crushed concrete in different disposal ways. This parameter governs the carbonation reaction determined by the exposed surface area, thereby directly influencing both the rate and the ultimate extent of CO_2 uptake. Based on the survey data from our previous research[12], the particle size distributions for the three disposal methods were categorized into four groups. RCA for new concrete are below 5 mm, 5–10 mm, 11–20 mm, and 21–32 mm. For the second method, RCA for Road base materials and others are below 1 mm, 1–10 mm, 10–30 mm, and above 30 mm. For landfilling and stacking are below 10 mm, 10–30 mm, 30–50 mm, and above 50 mm. This parameter is modeled using a uniform distribution[67,68], see Data 5.2 in Supplementary Table2.

(3) Carbonation rate coefficients in disposal stage

During the waste disposal phase, the carbonation rate coefficients for concrete materials should be determined according to the specific environmental conditions summarized in Tables S1 and S2. For concrete that is reused (RCA for new cement concrete and Road base materials and others), the coefficient should correspond to the relevant building environment, whereas for landfill disposal, it should reflect the conditions of the buried environment.

(4) Carbonation time

This parameter specifies the full life-cycle duration of cement to be used in the model. To ensure a complete accounting of cement carbonation, the value should be set such that it exceeds the number of years from the earliest recorded national cement use to the reporting year. In this study, we set the carbonation time as 200 years, allowing the model to output annual carbonation absorption factors for each year over the 200-year period.

Supplementary Note 5: Comparison of annual cement carbonation sink derived from different activity data time spans.

Human use of cement spans more than 2,000 years, national-level cement statistics and associated carbon emission inventories typically start from 1928[3], providing 95 years of data up to 2024. In existing datasets, cement records for the United States and Sweden can be traced back to 1880 and 1908, respectively. As shown in the figure S4 and S5, differences in the starting year of activity data lead to variations in cumulative carbonation by the reporting year. For example, when calculations for the United States begin in 1880, the annual carbon sequestration in 1983 is 5.2 Mt CO_2 higher than when starting from 1928, resulting in a cumulative difference of 189 Mt CO_2. For Sweden, the largest difference occurs in 1985, with an annual carbon sequestration discrepancy of approximately 0.07 Mt CO_2 and a cumulative difference of 2.8 Mt CO_2.

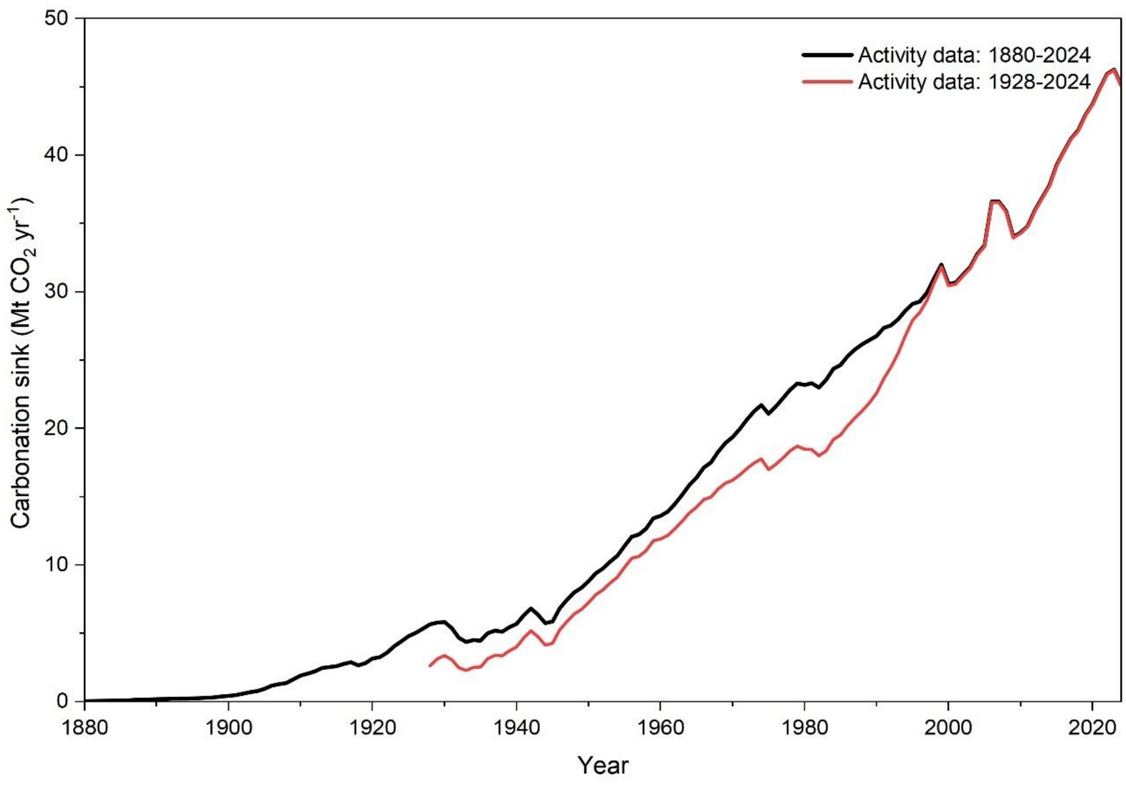

Fig. S7: Carbonation sink in the United State under different activity data time spans.

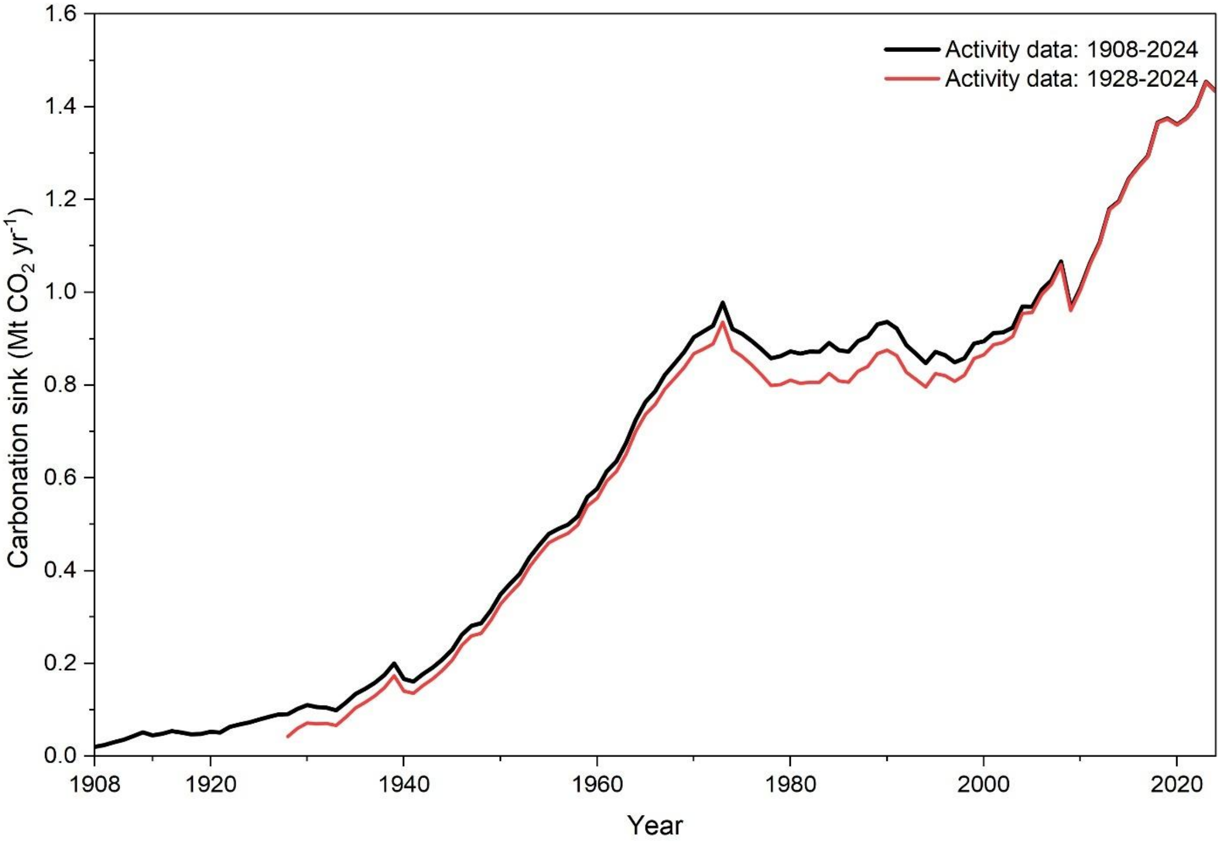

Fig. S8: Carbonation sink in the Sweden by different activity data time spans.

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