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Assessment of the Carbon Footprint in the Clinker-Based Cement Production Process

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Keywords	Abstract
Clinker Limestone Cement Thermodynamic modeling Carbon footprint	This paper analyzes the economic activities of several cement plants in the republic based on their ecological passports. It was noted that existing regulatory documents addressed the general environmental issues of individual industries, while the assessment of the carbon load in the cement production process remains open. Given these circumstances, it is emphasized that the formation of carbon-containing substances, including carbon dioxide, occurs during the high-temperature decomposition of calcium carbonate, the main raw material in cement production. Based on raw material consumption data at the Terek-Tash LLC plant (Novopokrovka village, Issyk-Ata District, Chui Region, Kyrgyzstan), a model chemical composition of cement clinker was compiled. It is emphasized that calcium oxide is not used directly in cement production, but is formed during the decomposition of limestone, meaning calcium carbonate was considered a carrier of carbon-containing substances. Accordingly, the concentration distribution of components and particles, including carbon-containing fragments formed at maximum entropy, was calculated. The established physicochemical and thermodynamic parameters of calcium carbonate degradation allowed us to determine the process direction, while the concentration distribution of various carbon-containing fragments in the gas phase revealed the total carbon footprint and the quantitative content of carbon oxides (CO, CO ₂) depending on temperature.
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1. INTRODUCTION

The production of cement products includes the following processes: preparation of raw materials (limestone – 75% and clay – 25%), grinding and converting them into homogeneous masses, evaporation of water from limestone and clay (2-100°C), dehydration of the mixture (100-430°C) and the formation of silicon, aluminum and iron oxides (hematite); destruction of limestone (800-1100°C) according to the scheme: $\text{CaCO}_3 - \text{CaO} + \text{CO}_2$ (Lavagna & Nistico, 2023). Exothermic reaction (1100-1300°C) and formation of disilicate phases: $2\text{CaO} + \text{SiO}_2 - 2\text{CaOSiO}_2$. Melting of the resulting mixture (1300-1450°C) and the transformation of disilicates into trisilicate and tetracalcium aluminoferrites: $2\text{CaO SiO}_2 + \text{CaO} - 3\text{CaO SiO}_2$; $3\text{CaO SiO}_2 + \text{CaO} + \text{Fe}_2\text{O}_3 - 4\text{CaO Al}_2\text{O}_3 \text{ Fe}_2\text{O}_3$; cooling and crystallization of mineral phases; grinding of clinker granules, mixing with gypsum and obtaining Portland cement

(CaO (63-66%), SiO₂ (21-24%), Al₂O₃ (4-8%), Fe₂O₃ (2-4%), other oxides (3-5%) (Taylor, 1997). It follows that the phase composition of cement clinker consists of four minerals: tricalcium silicate (C₃S or alite); dicalcium silicate (C₂S or belite); tricalcium aluminate (C₃A); tetracalcium aluminoferrite (C₄AF or ferrite) (Van Oss, 2005). During the destruction of limestone, carbon dioxide is released. One ton of cement produced globally corresponds to an average of 0.6 tons of CO₂, i.e., global cement production contributes approximately 7-8% of the CO₂ content of carbon dioxide in the gas phase, and accordingly has a anthropogenic impact on climate change (UN IPCC, 2021; GCCA, 2025; Lavagna & Nistico, 2023). It is noted that according to the Global Carbon Project (Andrew, 2019), the carbon footprint in 2023 amounted to 1.57 billion tons of CO₂, which is associated with the growth of global cement production in China, the USA, India and other countries (Fig. 1) (Andrew, 2019), including in the Kyrgyz Republic.

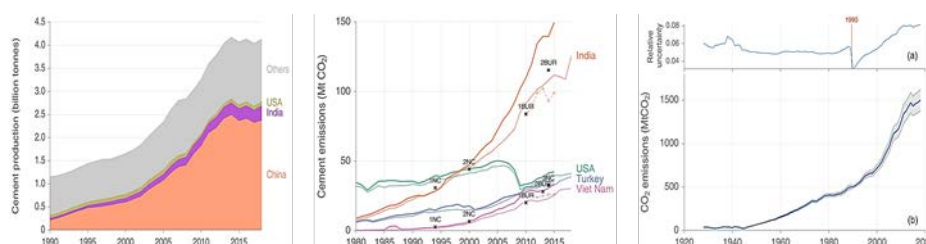


Fig. 1. Major cement producers and global CO₂ emissions from cement products (Andrew, 2019)

2. MATERIAL AND METHOD

The paper analyzes the economic activities of several cement enterprises in the republic and notes that the assessment of the carbon footprint of the cement production process in existing regulatory documents remains unclear. In this regard, it is emphasized that the anthropogenic impact of various fuels used in cement production significantly impacts carbon dioxide emissions into the environment. Given these circumstances, when calculating the carbon footprint, CO₂ emission factors (kg CO₂/l) should be taken into account: for gasoline – 2.31; diesel – 2.68; and fuel oil – 3.2 (Shestakov et al., 2024). Accordingly, the carbon footprint taking into account the full life cycle of cement production includes the following calculation stages (Shestakov et al., 2024): Obtaining raw materials (production): $CF_{prod.} = \sum(V_i^{raw\ mat.} \cdot EC_i^{raw\ mat.})$, i – types of road materials (bitumen, cement, inert materials); $EC_i^{raw\ mat.}$ – raw material emission coefficient; Transportation: $CF_{trans.} = \sum(L_j \cdot m_j \cdot EC_j^{trans.})$; L_j – cargo delivery distance; m_j – cargo mass; $EC_j^{trans.}$ – transport emission coefficient; j – mode of transport or its route (road transport, rail transport); Construction: $CF_{constr.} = \sum(t_k \cdot EC_k^{fuel})$, t_k – operating time of the k -th machine; EC_k^{fuel} – fuel emission coefficient; k – types of construction equipment (excavator, roller, motor grader, etc.); Operation: $CF_{oper.} = \sum(NR_l \cdot EM_l^{repair})$, NR – number of repairs, l – repair works or types of maintenance (covering, pit reclamation); EM_l^{repair} – emission of repair works; Reconstruction/liquidation: $CF_{liq.} = \sum(V_m^{dest.} \cdot EC_m^{mat.}) + \sum(V_n^{recyc.} \cdot P)$, $V_m^{liq.}$ – volume of destruction; $EC_m^{mat.}$ – emission coefficient of material; $V_n^{recyc.}$ – volume of recycling; P – emission reduction due to recycling; m and n – types of materials and processes associated with demolition and recycling. In connection with the above, it is noted that in the process of cement production, the content of carbon-containing substances in the gas phase is mainly determined by the concentration of carbon dioxide due to the destruction of limestone.

Therefore, at this stage we established the physicochemical (Cp, Mu, Lt, Pr, z) and thermodynamic parameters (S, I, U) of the cement clinker destruction process and determined the concentration distribution of various carbon-containing substances in the gas phase, identifying the total carbon footprint in individual fragments and subsequently calculating the quantitative content of carbon

oxides (CO , CO_2) depending on temperature. The calculations were carried out by thermodynamic modeling of the cement clinker destruction process at the maximum entropy of the system. The logarithms of individual substances and the weight fraction of chemical elements in the cement mixture (M_m) were taken as unknowns, and the problem was reduced to determining the M_c fragments using the iteration method (Trusov et al., 1982; Sinyarev et al., 1982).

3. RESULTS AND DISCUSSION

Currently, there are five cement plants operating in the republic: Kant TShP, Terek-Tash, Aravan, Sinzhi Pirim, and South Kyrgyz (Renaud, 2025). According to ecological passports, the Kant cement plant's production capacity is 1.1 million tons per year (United Cement Group, 2026). The daily capacity of the Terek-Tash cement plant for the production of Portland cement is 4,800 tons, and the annual capacity is 1.543 million tons. The Sinzhi Pirim Cement Plant is located in the Kerme-Too rural area. The Aravan Cement Plant produces Portland cement (M400-D20, PC500 D0, PC500 D20, CEM I-32.5). The annual capacity is 250,000 tons, producing 1 million tons of cement per year (AAA Group, 2026). The South-Kyrgyz Cement Plant produces cement using the dry process (1 million tons per year) (JSC "YUKTs", 2026).

The paper examines the production activities of the Terek-Tash cement plant (Chui region, Issyk-Ata district, Novopokrovka village). At the plant, during the cement production process, the clinker-gypsum-ash system is considered and the raw material consumption is taken into account: clinker – 1196.999 thousand tons/year; 3800 tons/day; 158.3 tons/hour; gypsum (CaSO_4) – 76.534 thousand tons/year; 243 tons/day; 10.1 tons/hour; coal ash from TPP in Bishkek – 244.91 thousand tons/year; 777.5 tons/day; 32.4 tons/hour. In the system, calcium oxide is produced during the thermal decomposition of limestone (CaCO_3) – 15.42 thousand tons/year; 38.9 tons/day; 1.6 tons/hour; coal as fuel – 7900 tons/year; 25 tons/day. General chemical composition of clinker (weight%): C_3S (30-50%); Ca_3SiO_5 (3CaO SiO_2), C_2S (20-45%); Ca_2SiO_4 (2CaO SiO_2), C_3A (8-12%); $\text{Ca}_3\text{Al}_2\text{O}_6$ ($3\text{CaO Al}_2\text{O}_3$), C_4AF (6-10%); $\text{Ca}_4\text{Al}_2\text{Fe}_2\text{O}_{10}$; $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ (4-8%); K (<2, K_2O); N (<2 Na_2O); by individual oxides (weight%): CaO (58-68), SiO_2 (16-26), Al_2O_3 (4-8), Fe_2O_3 (2-5), MgO (1-4), SO_3 (0.1-2.5) (JSC "Terek-Tash", 2025).

In the Terek-Tash plant, Portland cement is produced mainly on the basis of clinker (avg. wt. %) [3]: CaO – 64.5; SiO_2 – 22.5; Al_2O_3 – 6.0; Fe_2O_3 – 3, other oxides – 4, total – 100, where the chemical composition of cement is (wt.%): CaO – 64.5; SiO_2 – 22.5; Al_2O_3 – 6%; Fe_2O_3 – 3; K_2O – 1; Na_2O – 1; MgO – 1; SO_3 – 1 [3]. In this case, the matrix for calculating the carbon load of products based on cement clinker was (g): CaCO_3 – 115.18; SiO_2 – 22.5; Al_2O_3 – 6.0; Fe_2O_3 – 3.0; K_2O – 1.0; Na_2O – 1.0; MgO – 1.0; SO_3 – 1.0.

It is noted that cement production is determined by a carbon footprint, i.e., the emission of carbon dioxide (CO_2) into the environment. In order to determine the physicochemical (C_p , μ , L_t , P_r , z) and thermodynamic parameters (S , I , U) of the cement clinker destruction process, and to establish the concentration distribution of various carbon-containing substances in the gas phase with the identification of the total carbon footprint in individual fragments, calculations were carried out within a temperature change from 300 to 1500°C, taking into account a number of processes: evaporation-dehydration-heating-release (CO_2)-formation of various silicate phases (Tables 1-3, Figures 1-3). Below are the results on the destruction of cement clinker and the concentration distribution of components and particles depending on temperature.

Table 1. Destruction of cement clinker and concentration distribution of components and particles depending on temperature. Composition of cement clinker (g): $(\text{CaCO}_3 - 115.18) + (\text{SiO}_2 - 22.5) + (\text{Al}_2\text{O}_3 - 6.0) + (\text{Fe}_2\text{O}_3 - 3.0) + (\text{K}_2\text{O} - 1.0) + (\text{Na}_2\text{O} - 1.0) + (\text{MgO} - 1.0) + (\text{SO}_3 - 1.0)$; elemental composition, mol/kg: Ca - 7.637, C - 7.637, O - 30.019, Si - 2.485, Al - 0.781, Fe - 0.249, K - 0.141, Na - 0.214, Mg - 0.165, S - 0.083, $T = 300\text{-}3000\text{ K}$, $P = 0.1\text{ MPa}$

$T = 1200\text{ K}$

U=-10587.4	S=3.459	I=-10530.1	Cp=1.127
Mu=0.00004	Pr=0.720	z=0.664	Lt=0.080

concentration (mol/kg)

$\text{O} = 0.451 \cdot 10^{-9}$	$\text{O}_2 = 0.424 \cdot 10^{-4}$	$\text{SO} = 0.102 \cdot 10^{-10}$	$\text{SO}_2 = 0.279 \cdot 10^{-4}$
$\text{SO}_3 = 0.168 \cdot 10^{-7}$	$\text{CO} = 0.5641 \cdot 10^{-4}$	$\text{CO}_2 = 7.6371$	$\text{Al}_2\text{O}_{3(c)} = 0.131$
$\text{Fe}_2\text{O}_{3(c)} = 0.124$	$\text{MgAl}_2\text{O}_{4(c)} = 0.1$	$\text{CaO}_{(c)} = 3.9094$	$\text{Ca}_3\text{Si}_2\text{O}_{7(c)} = 1.24$
$\text{Na} = 0.522 \cdot 10^{-7}$	$\text{NaO} = 0.518 \cdot 10^{-11}$	$\text{Na}_2\text{SO}_{4(c)} = 0.01$	$\text{Na}_2\text{SO}_4 = 0.110 \cdot 10^{-5}$
$\text{NaAlO}_{2(c)} = 0.189$	$\text{K} = 0.234 \cdot 10^{-7}$	$\text{KO} = 0.474 \cdot 10^{-10}$	$\text{K}_2\text{SO}_{4(c)} = 0.070$
$\text{K}_2\text{SO}_4 = 0.483 \cdot 10^{-5}$	$\text{K}_2\text{CO}_3 = 0.1 \cdot 10^{-7}$	$\text{K}^+ = 0.133 \cdot 10^{-11}$	-

$T = 1250\text{ K}$

U=-10533.9	S=3.506	I=-10473.5	Cp=1.135
Mu=0.00004	Pr=0.721	z=0.664	Lt=0.083

concentration (mol/kg)

$\text{O} = 0.197 \cdot 10^{-8}$	$\text{O}_2 = 0.106 \cdot 10^{-3}$	$\text{SO} = 0.777 \cdot 10^{-10}$	$\text{SO}_2 = 0.997 \cdot 10^{-4}$
$\text{SO}_3 = 0.643 \cdot 10^{-7}$	$\text{CO} = 0.111 \cdot 10^{-3}$	$\text{CO}_2 = 7.637$	$\text{Al}_2\text{O}_{3(c)} = 0.131$
$\text{Fe}_2\text{O}_{3(c)} = 0.125$	$\text{MgAl}_2\text{O}_{4(c)} = 0.1$	$\text{CaO}_{(c)} = 3.909$	$\text{Ca}_3\text{Si}_2\text{O}_{7(c)} = 1.24$
$\text{Na} = 0.201 \cdot 10^{-6}$	$\text{NaO} = 0.3 \cdot 10^{-10}$	$\text{Na}_2\text{SO}_{4(c)} = 0.01$	$\text{Na}_2\text{SO}_4 = 0.4 \cdot 10^{-5}$
$\text{NaAlO}_{2(c)} = 0.18$	$\text{K} = 0.979 \cdot 10^{-7}$	$\text{KO} = 0.283 \cdot 10^{-9}$	$\text{K}_2\text{SO}_{4(c)} = 0.070$
$\text{K}_2\text{SO}_4 = 0.1 \cdot 10^{-4}$	$\text{K}_2\text{CO}_3 = 0.3 \cdot 10^{-7}$	$\text{K}^+ = 0.660 \cdot 10^{-11}$	-

$T = 1300\text{ K}$

U=-10480	S=3.551	I=-10416.4	Cp=1.143
Mu=0.00004	Pr=0.721	z=0.664	Lt=0.086

concentration (mol/kg)

$\text{O} = 0.785 \cdot 10^{-8}$	$\text{O}_2 = 0.257 \cdot 10^{-3}$	$\text{SO} = 0.477 \cdot 10^{-9}$	$\text{SO}_2 = 0.312 \cdot 10^{-3}$
$\text{SO}_3 = 0.220 \cdot 10^{-6}$	$\text{CO} = 0.201 \cdot 10^{-3}$	$\text{CO}_2 = 7.637$	$\text{Al}_2\text{O}_{3(c)} = 0.131$

$\text{Fe}_2\text{O}_{3(c)} = 0.125$	$\text{MgAl}_2\text{O}_{4(c)} = 0.1$	$\text{CaO}_{(c)} = 3.909$	$\text{Ca}_3\text{Si}_2\text{O}_{7(c)} = 1.24$
$\text{Na} = 0.685 \cdot 10^{-6}$	$\text{NaO} = 0.167 \cdot 10^{-9}$	$\text{Na}_2\text{SO}_{4(c)} = 0.01$	$\text{Na}_2\text{SO}_4 = 0.1 \cdot 10^{-4}$
$\text{NaAlO}_2(c) = 0.18$	$\text{K} = 0.359 \cdot 10^{-6}$	$\text{KO} = 0.148 \cdot 10^{-8}$	$\text{K}_2\text{SO}_{4(c)} = 0.070$
$\text{K}_2\text{SO}_4 = 0.4 \cdot 10^{-4}$	$\text{K}_2\text{CO}_3 = 0.8 \cdot 10^{-7}$	$\text{K}^+ = 0.295 \cdot 10^{-10}$	$\text{SO}_2^- = 0.15 \cdot 10^{-11}$

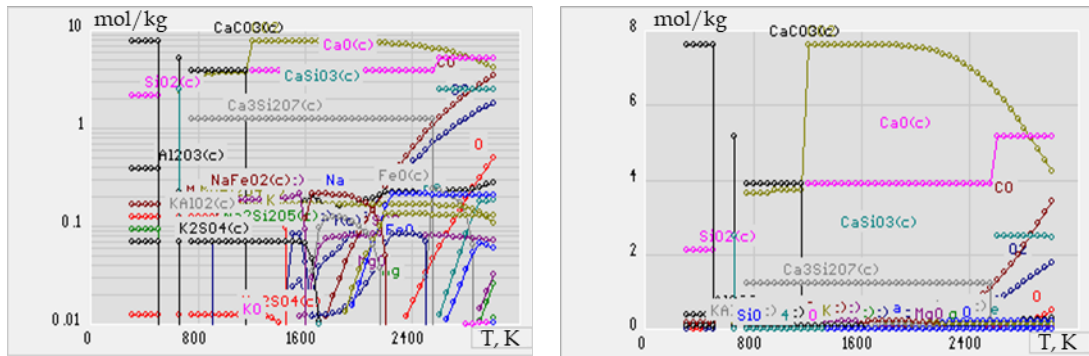


Fig. 2. Concentration distribution of the main components and particles (mol/kg) during the destruction of cement clinker depending on temperature (K), $P=0.1$ MPa

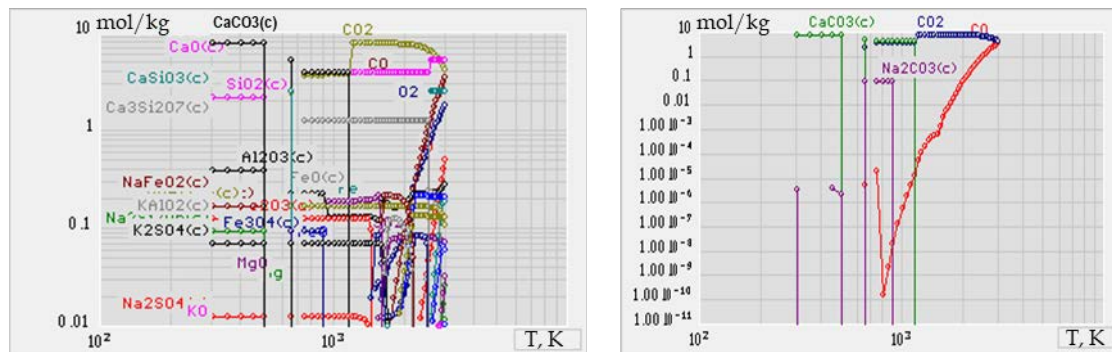


Fig. 3. Concentration distribution of calcium, silicon, aluminum, sodium and potassium containing components and particles (mol/kg) during the destruction of cement clinker depending on temperature (K), $P=0.1$ MPa

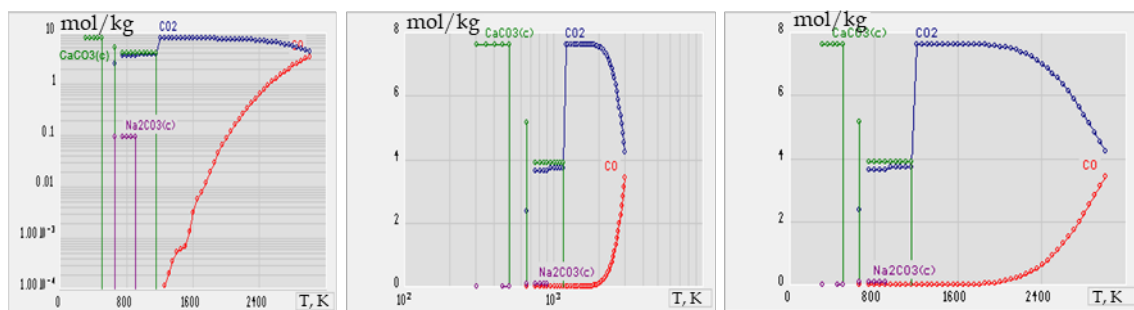


Fig. 4. Concentration distribution of calcium carbonate, carbon oxide and carbon dioxide (mol/kg) during the destruction of cement clinker depending on temperature (K), $P=0.1$ MPa

The obtained results showed that the following carbon-containing components are formed during cement production: CO , CO_2 , C_2O , CS , COS , CaCO_3 , Na_2CO_3 , K_2CO_3 . In this case, the

destruction of limestone is caused by the release of CO_2 (7.637 mol/kg), where the carbon load is 91.644 g C, i.e., based on the total carbon content, the load of carbon oxide and dioxide in 1 kg of the gas phase was determined (214 g CO or 336 g CO_2) (Tables 2 and 3).

Table 2. Concentration distribution of carbon-containing components and particles in the gas phase (mol/kg) during the destruction of cement clinker depending on temperature (K)

T, K	CO	CO_2	C_2O	CS	COS	$\text{CaCO}_3(\text{c})$	$\text{Na}_2\text{CO}_3(\text{c})$	K_2CO_3
300	$2.3 \cdot 10^{-21}$	$2.3 \cdot 10^{-21}$	$2.3 \cdot 10^{-21}$	$2.3 \cdot 10^{-21}$	$2.3 \cdot 10^{-21}$	91.68	$3.9 \cdot 10^{-5}$	$2.3 \cdot 10^{-21}$
500	$2.3 \cdot 10^{-21}$	$2.3 \cdot 10^{-21}$	$2.3 \cdot 10^{-21}$	$2.3 \cdot 10^{-21}$	$2.3 \cdot 10^{-21}$	91.6	$2.5 \cdot 10^{-5}$	$2.3 \cdot 10^{-21}$
700	$2.6 \cdot 10^{-9}$	28.7	$2.3 \cdot 10^{-21}$	$2.3 \cdot 10^{-21}$	$1.54 \cdot 10^{-19}$	61.8	1.14	$3.4 \cdot 10^{-17}$
900	$2.4 \cdot 10^{-7}$	43.6	$2.3 \cdot 10^{-21}$	$2.3 \cdot 10^{-21}$	$2.3 \cdot 10^{-21}$	46.9	1.14	$3.96 \cdot 10^{-11}$
950	$1.6 \cdot 10^{-6}$	44.7	$2.3 \cdot 10^{-21}$	$2.3 \cdot 10^{-21}$	$2.3 \cdot 10^{-21}$	46.9	$1.2 \cdot 10^{-29}$	$2.4 \cdot 10^{-10}$
1000	$7.2 \cdot 10^{-6}$	44.7	$2.3 \cdot 10^{-21}$	$2.3 \cdot 10^{-21}$	$2.3 \cdot 10^{-21}$	46.9	$1.2 \cdot 10^{-29}$	$9.3 \cdot 10^{-10}$
1050	$2.4 \cdot 10^{-5}$	44.7	$2.3 \cdot 10^{-21}$	$2.3 \cdot 10^{-21}$	$3.9 \cdot 10^{-20}$	46.9	$1.2 \cdot 10^{-29}$	$3.2 \cdot 10^{-9}$
1100	$6.4 \cdot 10^{-5}$	44.7	$2.3 \cdot 10^{-21}$	$2.3 \cdot 10^{-21}$	$1.2 \cdot 10^{-18}$	46.9	$1.2 \cdot 10^{-29}$	$9.86 \cdot 10^{-9}$
1150	$1.5 \cdot 10^{-4}$	44.7	$2.3 \cdot 10^{-21}$	$2.3 \cdot 10^{-21}$	$2.2 \cdot 10^{-17}$	46.9	$1.2 \cdot 10^{-29}$	$2.7 \cdot 10^{-8}$
1200	0.001	91.65	$2.3 \cdot 10^{-21}$	$2.3 \cdot 10^{-21}$	$5.3 \cdot 10^{-16}$	$1.2 \cdot 10^{-29}$	$1.2 \cdot 10^{-29}$	$1.6 \cdot 10^{-7}$
1250	0.001	91.65	$2.3 \cdot 10^{-21}$	$2.3 \cdot 10^{-21}$	$4.4 \cdot 10^{-15}$	$1.2 \cdot 10^{-29}$	$1.2 \cdot 10^{-29}$	$4.1 \cdot 10^{-7}$
1300	0.002	91.64	$2.3 \cdot 10^{-21}$	$2.3 \cdot 10^{-21}$	$2.8 \cdot 10^{-14}$	$1.2 \cdot 10^{-29}$	$1.2 \cdot 10^{-29}$	$9.7 \cdot 10^{-7}$
1350	0.004	91.64	$2.3 \cdot 10^{-21}$	$2.3 \cdot 10^{-21}$	$1.4 \cdot 10^{-13}$	$1.2 \cdot 10^{-29}$	$1.2 \cdot 10^{-29}$	$2.1 \cdot 10^{-6}$
1400	0.006	91.64	$2.3 \cdot 10^{-21}$	$2.3 \cdot 10^{-21}$	$4.3 \cdot 10^{-13}$	$1.2 \cdot 10^{-29}$	$1.2 \cdot 10^{-29}$	$3.9 \cdot 10^{-6}$
1450	0.007	91.64	$2.3 \cdot 10^{-21}$	$2.3 \cdot 10^{-21}$	$4.4 \cdot 10^{-13}$	$1.2 \cdot 10^{-29}$	$1.2 \cdot 10^{-29}$	$7.01 \cdot 10^{-6}$
1500	0.008	91.64	$2.3 \cdot 10^{-21}$	$2.3 \cdot 10^{-21}$	$5.3 \cdot 10^{-13}$	$1.2 \cdot 10^{-29}$	$1.2 \cdot 10^{-29}$	$1.2 \cdot 10^{-5}$
1550	0.015	91.63	$2.3 \cdot 10^{-21}$	$6.2 \cdot 10^{-21}$	$3.6 \cdot 10^{-12}$	$3.4 \cdot 10^{-29}$	$3.4 \cdot 10^{-29}$	$2.7 \cdot 10^{-5}$
1600	0.037	91.61	$2.3 \cdot 10^{-21}$	$1.4 \cdot 10^{-19}$	$2.6 \cdot 10^{-11}$	$1.2 \cdot 10^{-29}$	$1.2 \cdot 10^{-29}$	0.0001
1650	0.066	91.58	$2.3 \cdot 10^{-21}$	$2.5 \cdot 10^{-18}$	$1.8 \cdot 10^{-10}$	$1.2 \cdot 10^{-29}$	$1.2 \cdot 10^{-29}$	0.0002
1700	0.089	91.56	$2.3 \cdot 10^{-21}$	$1.25 \cdot 10^{-17}$	$4.96 \cdot 10^{-10}$	$1.2 \cdot 10^{-29}$	$1.2 \cdot 10^{-29}$	0.0003

Table 3. Distribution of carbon footprint (g) in the gas phase at the temperature of destruction of cement clinker

T, K	1500		C, gram
C	mol/kg	$1,9 \cdot 10^{-22}$	$2,3 \cdot 10^{-21}$
CO	mol/kg	0,001	$7,98 \cdot 10^{-3}$
CO ₂	mol/kg	7,637	91,64
C ₂ O	mol/kg	$1,9 \cdot 10^{-22}$	$2,3 \cdot 10^{-21}$
CS	mol/kg	$1,9 \cdot 10^{-22}$	$2,3 \cdot 10^{-21}$
COS	mol/kg	$4,4 \cdot 10^{-14}$	$5,3 \cdot 10^{-13}$
CaCO ₃	mol/kg	$1 \cdot 10^{-30}$	$1,2 \cdot 10^{-29}$
Na ₂ CO ₃	mol/kg	$1 \cdot 10^{-30}$	$1,2 \cdot 10^{-29}$
K ₂ CO ₃	mol/kg	$9,97 \cdot 10^{-7}$	$1,2 \cdot 10^{-5}$

Reducing carbon dioxide emissions in cement production can be achieved by using clinker production technology based on coal ash or blast furnace slag (Suraneni, 2021; Oluwafemi Ezekiel et al., 2024), as well as by burning alternative fuels, in particular oxygen (Williams et al. 2024) with carbon recovery and conservation (CCS), waste heat recycling (WHR) (Oluwafemi Ezekiel et al., 2024) and the introduction of a carbon tax.

4. CONCLUSION

In the process of cement production, carbon-containing substances, including carbon dioxide, are formed during the high-temperature decomposition of calcium carbonate, which is used as the main raw material. Based on raw material consumption data at the Terek-Tash plant, a model chemical composition of cement clinker was developed and the concentration distribution of components and particles, including carbon-containing fragments formed at maximum entropy, was calculated. The established physicochemical and thermodynamic parameters of calcium carbonate degradation allowed us to determine the process direction, while the concentration distribution of various carbon-containing fragments in the gas phase revealed the total carbon footprint and the quantitative content of carbon oxides (CO, CO₂) depending on temperature.

AUTHOR CONTRIBUTIONS

Author Contributions: Damira Sambaeve: Writing – review and editing, Supervision, Investigation, Data curation. Chynara Jayloobek kyzy: Sources, Research. Zarlik Maimekov: Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. Miraida Turgunbekova: Sources, Research. Janarbek Izakov: Review and editing. All authors have read and agreed to the published version of the manuscript.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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