ENIVRONMENTAL SYSTEMS AND SOCIETIES EXTENDED ESSAY

To what extent do different types of cement production processes (CEM I, II, III, IV, and V) affect the mass of carbon dioxide emitted (metric tons) in the construction industry of Turkey between the years 2012 and 2023?

Word Count: 3668

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1. Introduction

1.1 Construction Industry in the World

Cement, a fundamental material in construction, plays a crucial role in the development and infrastructure of modern societies. It serves as the key ingredient in concrete, the most widely used man-made material globally, forming the backbone of buildings, bridges, roads, and other critical structures. [Global Cement and Concrete Association, GCCA, 2020] The construction industry is a major driver of economic growth worldwide, fuelling urbanization and industrial development. However, this industry also significantly affects the environment due to its high demand for raw materials, energy consumption, and carbon emissions.

1.2 Construction Industry in Turkey

In Turkey, where the construction industry is a vital part of the economy, the demand for cement has increased due to rapid urbanization and infrastructure development. The country's cement industry has been expanding rapidly to meet these demands. However, this growth comes with increased environmental concerns, particularly regarding carbon emissions. Understanding the environmental impact of cement production in Turkey is essential for developing sustainable practices that balance economic growth with ecological responsibility.

2. Background Information

2.1. Cement Production

Cement production is a crucial industrial process that involves the extraction and processing of raw materials, primarily limestone and clay, to produce cement. The production process requires high temperatures and significant energy inputs. The key component of cement is clinker, which is produced through the calcination process in furnaces heated to approximately 1,450°C. [Cembureau, 2024] Once clinker is formed, it is ground with other materials to create different types of cement. The efficiency and environmental impact of cement production depend on the choice of raw materials, energy sources, and technological advancements.

2.2. Cement Types

There are different types of cement, classified as CEM I through CEM V, each varying in composition and raw materials. CEM I, also known as "Ordinary Portland Cement", is the most common type and is known for its high clinker content. In contrast, CEM II, III, IV, and V incorporate supplementary cementitious materials (SCMs) such as fly ash (a by-product of the coal-fired power plants), slag (a by-product from the steel industry), and pozzolans, which reduce the clinker content. [Cembureau, 2024]

2.3. Carbon Emission during Cement Production

Cement production is responsible for approximately 8% of CO2 emissions globally. [World Economic Forum, 2024] [Fakta o Klimatu, n.d.] The production process typically uses fossil fuels as an energy source, in ovens heated to approximately 1,450°C. It involves heating a large number of limestone (calcium carbonate) to produce calcium oxide, which is called "clinker" in the industry. Carbon dioxide is a by-product of this reaction. This process of burning calcium carbonate is called "calcination". The formula for calcination is as follows:

$$CaO_3 \rightarrow CaO + CO_2$$ [Fakta o Klimatu, n.d.] [Greenspec, n.d.]

As a result of the calcination process, approximately 785 kilograms of carbon dioxide is emitted for each metric ton of clinker produced. Since each type of cement contains different mass of clinker, the carbon emission from the production of each cement type will vary too.

Calcination process is responsible for approximately 60% of the carbon emission of cement production. [Cembureau, 2024] The remaining 40% comes from the extraction of limestone, transportation of materials to cement plants and construction sites, heating of the limestone and other various aspects.

Heating the limestone requires great amounts of energy. To provide this energy, fossil fuels are burnt. The sum of calcination process and heating result in an overall carbon dioxide emission of approximately 853 kilograms per 1 metric ton of clinker produced. However, calcium oxide only consists 66% of clinker. [NOAA, 2024] That is why in the calculations section, the values are multiplied by 0.66 to account for this.

2.4. The Effects of Carbon Dioxide on the Environment

Carbon dioxide (CO_2) is a greenhouse gas that significantly affects the environment by contributing to global warming and climate change. When CO_2 is released into the atmosphere, it traps heat from the sun, creating a greenhouse effect that leads to higher global temperatures. This warming effect results in various environmental changes, including melting polar ice caps and glaciers, rising sea levels, and more frequent and severe weather events such as hurricanes, droughts, and heatwaves. Additionally, increased atmospheric CO_2 levels lead to ocean acidification. Carbon dioxide dissolves in seawater to form carbonic acid, which harms marine life, particularly organisms with calcium carbonate shells and skeletons, such as corals and molluscs. The cumulative impact of these changes is a significant risk to biodiversity, ecosystems, and the human society. [The Ocean Portal Team, 2023]

2.5. Sustainable Development Goals Related With This Exploration

The Sustainable Development Goals are a set of seventeen global goals designed achieve a better and more sustainable future for everyone. Adopted by the United Nations General Assembly in 2015, they aim to address the most pressing challenges facing humanity and the planet by 2030. This topic is extremely important as it concerns three sustainable goals in total. Which are; 9-industry, innovation and infrastructure, 11-sustainable cities and communities and 13-climate action. [United Nations, n.d.]

Figure 1– Figure showing three sustainable development goals (SDGs). 9-Indsutry, Innovation and Infrastructure, 11-Sustainable Cities and Communities and 13- Climate Action

SDG 9 - Industry, Innovation, and Infrastructure emphasizes the need for strong infrastructure and sustainable industrialisation. The cement industry must adopt innovative technologies to reduce emissions while maintaining production efficiency. This supports economic growth while mitigating environmental harm.

SDG 11 - Sustainable Cities and Communities highlights the importance of sustainable urban development. Cement is essential for building cities, roads, and infrastructure, yet traditional production methods threaten urban air quality and contribute to the global warming. Cement choices can have an effect on how sustainable our cities are.

SDG 13 - Climate Action directly relates to the cement sector's carbon footprint. Traditional cement production is a major contributor to global carbon dioxide emissions, worsening climate change. That is why this SDG relates to the topic. Policies promoting low-carbon cement production can significantly contribute to climate protection strategies.

2.6. Research Question:

To what extent do different types of cement production process (CEM I, II, III, IV, and V) affect the mass of carbon dioxide emitted (metric tons) in construction industry of Turkey between the years 2012 and 2023?

2.7. Aim of this Study

This exploration aims to analyse the effect of different types of cement production on the carbon dioxide emissions in Turkey to shed light on the environmental effects of cement production on the environment. This way, the type with the lowest carbon dioxide emissions could be pointed out and promoted to be used more. Potentially encouraging new studies to be made in order to develop better cement types that have even less carbon dioxide emissions.

2.8 Hypothesis

Null Hypothesis H_0: There will be no statistically significant difference between the carbon dioxide emission amounts of different types of cement.

Alternative Hypothesis H_1: there will be statistically significant difference between the carbon dioxide emission amounts of different types of cement.

3. Methodology

3.1. Method Development

Even though there are some research done before on this topic, there are no researches done regarding the carbon dioxide emissions of different types of cement in Turkey. Therefore, I came up with my method to obtain data. I will be doing interpretations based on this method. There exists no data on the distribution of carbon emission among different types of cement. Therefore, I will take data from “TÜRKÇİMENTO”, a non-governmental organisation that aims to find solutions to the problems in the cement sector. [Türkiye Çimento Sanayicileri Birliği, n.d.] There is data available dating back to 1999, however it is better to only take data after from 2012. The reason for that is, in 2012, the Turkish Standards Institution published the new standards for cement under the name “TS EN 197-1”. I will only take data that is after 2012 in order to come up to a better conclusion. The data taken from TÜRKÇİMENTO shows the total sales of each cement type made in a year. Here, I will make an assumption saying that 100 percent of the cement produced is sold. Next, I will examine the clinker percentages of every cement type. After that, I will calculate the carbon dioxide emission of each cement type based on the aforementioned ratio. Finally, I will come up to a conclusion and find out which type is the most and which is the least harmful to the environment and discuss how we can take action to reduce carbon dioxide emissions caused by cement production.

3.2. Variables

Independent Variable

- Different types of cement (CEM I, II, III, IV, and V)

Dependent Variable

- Carbon dioxide emission mass (metric tons)

Controlled Variables

- Assuming that all cement that is produced is sold. This is a controlled variable, because if it is not controlled by assuming, we would not be able to perform calculations.

3.3. Procedure:

1. The data of yearly cement sales will be taken from "TÜRKÇİMENTO". Only the data between the years 2012 and 2023 will be taken. Data for 2024 is not available yet.
2. It will be assumed that 100 percent of the cement produced is sold.
3. The average production mass will be calculated for each cement type. This will be done by summing up every subtype of each cement type and dividing by the number of subtypes.
4. For each cement type, the average clinker percent will be calculated by taking the chart as a reference.
5. The total clinker mass in each cement type will be calculated by multiplying the average clinker percent and the average number of cement production.
6. Next, the resulting number will be multiplied with 0.563 to get the mass of carbon dioxide emission. It is multiplied by 0.563 because for every 1000 kilograms of calcium oxide production, 853 kilograms of carbon dioxide is produced and calcium oxide consists of 66% of clinker. Thus, $0.66 \times 0.853 = 0.563$.

3.4. Evaluation of Ethical Issues, Risks and Justification of Resource

Environmental concerns: Since it is a secondary data exploration, there are no environmental concerns involved in it.

Justification of Resource: TÜRKÇİMENTO is non-governmental organisation that was established in 1957, indicating a long history and presence in the sector. Their R&D laboratories that have accreditations from TÜRKAK, which is the Turkish accreditation agency, this shows they are held to high standards. It is also a member of the "European Concrete Paving Association" (EUPAVE), the "European Cement Research Academy" (ECRA) and the "Global Cement and Concrete Association" (GCCA). These make TÜRKÇİMENTO a globally recognised organisation. [Türkiye Çimento Sanayicileri Birliği, n.d.] A sample screenshot is given on Table 1, the table shows the cement production data for the year 2023.

Table 1 – Screenshot of one of the original data tables taken from TÜRKÇİMENTO. https://www.turkcimento.org.tr/tr/istatistikler/cins

2023 yılı iç satışlarının cinslerine göre dağılımı

TON			Marmara	Ege	Akdeniz	Karadeniz	İç Anadolu	Doğu Anadolu	G.Doğu Anadolu	TOPLAM
Toplam İç Satış			14,834,256	6,268,007	12,127,052	7,096,197	13,093,810	5,720,725	5,852,100	64,992,147
CEM I		32.5								0
		%								0.00
		42.5	8,652,649	2,112,868	7,123,739	3,867,939	3,520,997	3,866,621	1,846,403	30,991,216
		%	58.33	33.71	58.74	54.51	26.89	67.59	31.55	47.68
		52.5	87,008	15,795	352,497	119	171,252		1,700,204	2,326,875
		%	0.59	0.25	2.91	0.00	1.31		29.05	3.58
CEM II	A-S	42.5	748,812		457,964	18,456	480,441			1,705,673
		%	5.05		3.78	0.26	3.67			2.62
	B-S	42.5	703,140							703,140
		%	4.74							1.08
	A-P	52.5			984,032					984,032
		%			8.11					1.51
	A-V	42.5				130,024				130,024
		%				1.83				0.20
		52.5	556,680							556,680
		%	3.75							0.86
	A-W	42.5		504	142,031			138,556		281,091
		%		0.01	1.17			2.42		0.43
	A-L	42.5	27			815,554	2,347,311	223,032		3,385,924
		%	0.00			11.49	17.93	3.90		5.21
	B-L	32.5			28,139			4,556		32,695
		%			0.23			0.08		0.05
		42.5					615			615
		%					0.00			0.00
	A-LL	32.5			54,070					54,070
		%			0.45					0.08
		42.5	287,880	1,024,688	1,704	144,360	3,425,062	109,309	318,663	5,311,666
		%	1.94	16.35	0.01	2.03	26.16	1.91	5.45	8.17
		52.5			146,422					146,422
		%			1.21					0.23
	B-LL	32.5	250,223	2,793	3,298		62,789		105,378	424,481
		%	1.69	0.04	0.03		0.48		1.80	0.65
		42.5	2,796		32,785		3,342			38,923
		%	0.02		0.27		0.03			0.06
	A-M	42.5	1,986,847	39,192	573,143	1,012,621	1,899,119	632,125	745,352	6,888,399
		%	13.39	0.63	4.73	14.27	14.50	11.05	12.74	10.60
		52.5	176,989						262,388	439,377
		%	1.19						4.48	0.68
	B-M	32.5	73,898		118,193	101,811	10,890	221,298	49,521	575,611
		%	0.50		0.97	1.43	0.08	3.87	0.85	0.89
		42.5	288,653	2,367,266	90,178				284,351	3,030,448
		%	1.95	37.77	0.74				4.86	4.66
	C-M	32.5		89,779	291,337		151,591		199,236	731,943
		%		1.43	2.40		1.16		3.40	1.13
		42.5		2,517						2,517
		%		0.04	0.00					0.00
CEM III	A	32.5				4,783				4,783
		%				0.07				0.01
		42.5			329,128	32,518				361,646
		%			2.71	0.46				0.56
	B	32.5				46,508				46,508
		%				0.66				0.07
CEM IV	A	32.5					70,717			70,717
		%					0.54			0.11
		42.5	35,890	13,034						48,924
		%	0.24	0.21						0.08
		52.5	8,828							8,828
		%	0.06							0.01
	B	32.5	686,529	85,690	1,013,527	780,635	768,811	374,627	306,019	4,015,838
		%	4.63	1.37	8.36	11.00	5.87	6.55	5.23	6.18
		42.5		513,764			139,023	150,601		803,388
		%		8.20			1.06	2.63		1.24
CEM V	A	32.5	204,349		149,677					354,026
		%	1.38		1.23					0.54
	B	32.5	82,443							82,443
		%	0.56							0.13
CEM VI	S-L	32.5				18,856				18,856
		%				0.27				0.03
	S-LL	32.5			218,111					218,111
		%			1.80					0.34
Diğer		32.5	587		12,559	122,013	17,545		34,585	187,289
		%	0.00		0.10	1.72	0.13		0.59	0.29
		42.5	28		4,518		24,305			28,851
		%	0.00		0.04		0.19			0.04
		52.5		117						117
		%		0.00						0.00

Risk Assessment: There are no risk concerns involved in this exploration.

Ethical Concerns: There are no ethical concern involved in this exploration.

4. Results

4.1. Raw Data

The raw data available shows the total mass of cement (metric tonnes) produced in Turkey throughout the years 2012 and 2023. The data for the year 2024 is not available yet.

Table 2 – Table showing the production mass, in metric tonnes, for each cement type from year 2012 to 2023.

	Cement Production Mass (metric tonnes)				
	Cement Type				
Years	CEM I	CEM II	CEM III	CEM IV	CEM V
2023	45,733,927	27,821,761	440,652	4,987,561	436,577
2022	43,680,978	23,371,346	374,450	4,522,911	792,825
2021	48,142,814	23,179,501	397,889	5,111,733	814,013
2020	43,705,685	19,846,258	461,345	5,040,957	1,393,570
2019	32,805,017	17,699,001	288,681	4,768,668	639,849
2018	42,789,536	21,339,713	581,073	5,743,186	677,457
2017	47,065,651	25,314,097	567,457	5,710,640	1,013,401
2016	42,544,084	24,638,299	590,861	5,528,598	653,432
2015	38,235,058	25,212,854	732,808	5,663,128	1,034,929
2014	36,929,400	25,519,740	1,023,911	6,105,013	1,078,410
2013	37,093,489	24,054,039	1,330,046	5,927,022	869,975
2012	32,411,081	21,733,104	1,160,278	5,985,377	892,034

The clinker percentage for each cement type is needed for the calculations too. Here is the table that shows the clinker percentage for each cement type and its subtype. This data was also taken from TÜRKÇİMENTO.

Table 3 – The table showing clinker percentage for each cement type. Data taken from TÜRKÇİMENTO.

Cement Type		Clinker Percentage (% mass)
CEM I	no subtype	95-100
CEM II	A-S	80-94
	B-S	65-79
	A-D	90-94
	A-P	80-94
	B-P	65-79
	A-Q	80-94
	B-Q	65-79
	A-V	80-94
	B-V	65-79
	A-W	80-94
	B-W	65-79
	A-T	80-94
	B-T	65-79
	A-L	80-94
	B-L	65-79
	A-LL	80-94
	B-LL	65-79
	A-M	80-94
	B-M	65-79
CEM III	A	35-64
	B	20-34
	C	5-19
CEM IV	A	65-89
	B	45-64
CEM V	A	40-64
	B	20-38

4.2. Calculations

First, production mass for each cement type will be averaged from the year 2012 to 2023. Then, the averaged value for each type will be multiplied by the clinker ratio to get the mass of clinker produced. After that, the clinker mass will be multiplied with 0.853 to find out how much carbon dioxide was emitted during the production of the cement.

The calculations will be done by using the following table. The table shows the clinker percent for each type of cement.

Calculating the average cement production results in the following table. A sample calculation is given for CEM III:

$$Average\ \text{CEM III production} = \frac{2023\ Production + 2022\ Prod. + \cdots + 2012\ Production}{Years}$$

$$= \frac{440652 + 374450 + 397889 + 461345 + 288681 + 581073 + 567457 + 590861 + 732808 + 1023911 + 1330046 + 1160278}{12}$$

= 662,479.92 which is approximately 662,454

Table 4 – Table showing the average cement production for each cement type. Averaged over 12 years, from 2012 to 2023

Cement Type	Average Cement Production (metric tonnes)
CEM I	40,765,560
CEM II	24,144,143
CEM III	662,454
CEM IV	5,341,233
CEM V	858,873

The average clinker percentage will be calculated for each sub-type of every cement type. Then, the average of the resulting value will be calculated for the actual average of the according cement type. A sample calculation is made for CEM III:

$$Average\ clinker\ of\ a\ subtype = \frac{Maximum\ value + Minimum\ value}{Number\ of\ values}$$

$$Average\ clinker\ percentage\ of\ \text{CEM III/A} = \frac{35 + 64}{2} = 49.5\%$$

$$Average\ clinker\ percentage\ of\ \text{CEM III/B} = \frac{20 + 24}{2} = 22\%$$

$$Average\ clinker\ percentage\ of\ \text{CEM III/C} = \frac{5 + 19}{2} = 12\%$$

Taking the average of all three of the subtypes of CEM III will result in the whole average for CEM III:

$$Average\ clinker\ percentage\ of\ \text{CEM III} = \frac{49.5 + 22 + 12}{3} = 27.38\%$$

Same process was repeated for each cement type to derive the following table. This table allows the calculations to be made easier.

Table 5 – Table showing the average clinker percentage for each cement type

Cement Type	Average Clinker Percentage (%)
CEM I	97.50
CEM II	80.16
CEM III	27.38
CEM IV	65.75
CEM V	40.50

What needs to be done now is multiplying the clinker percentage with the average production to get the average clinker production:

$$662{,}454 \times \frac{27.38}{100} = 181{,}380$$

Table 6 – Table showing the average clinker mass for each cement type

Cement Type	Average Clinker Mass Produced (metric tonnes)
CEM I	39,746,421
CEM II	19,353,945
CEM III	181,380
CEM IV	3,511,861
CEM V	347,844

This data is then multiplied by 0.563. This last calculation will result in the average carbon dioxide emission per year for each different cement type. By this means, we will be able to interpret the carbon dioxide emission mass of cement types. The processed data is as follows:

$$181{,}380 \times 0.563 = 102{,}117$$

4.3. Processed Data

Table 7 – Table showing the carbon dioxide emission mass for each cement type

	Carbon Dioxide Emission Mass (metric tonnes)				
	Cement Type				
Years	CEM I	CEM II	CEM III	CEM IV	CEM V
2023	25104496	12555983	67926	1846258	99546
2022	23977581	10547507	57721	1674257	180776
2021	26426794	10460927	61334	1892223	185607
2020	23991143	8956632	71116	1866024	317755
2019	18007494	7987573	44500	1765230	145895
2018	23488246	9630630	89572	2125970	154470
2017	25835512	11424272	87473	2113922	231071
2016	23353511	11119284	91081	2046535	148992
2015	20988179	11378581	112962	2096334	235979
2014	20271471	11517079	157835	2259908	245894
2013	20361543	10855607	205026	2194021	198367
2012	17791253	9808167	178856	2215622	203397

After the calculations, the table above is acquired. Taking the average for these results in the following table. The sample calculation s for CEM III:

$$\frac{67926 + 57721 + 61334 + 71116 + 44500 + 89572 + 87473 + 91081 + 112962 + 157835 + 205026 + 178856}{12}$$

$$= 102{,}117 \text{ tonnes of carbon dioxide}$$

Table 8 – Table showing the average carbon dioxide emission mass for each cement type

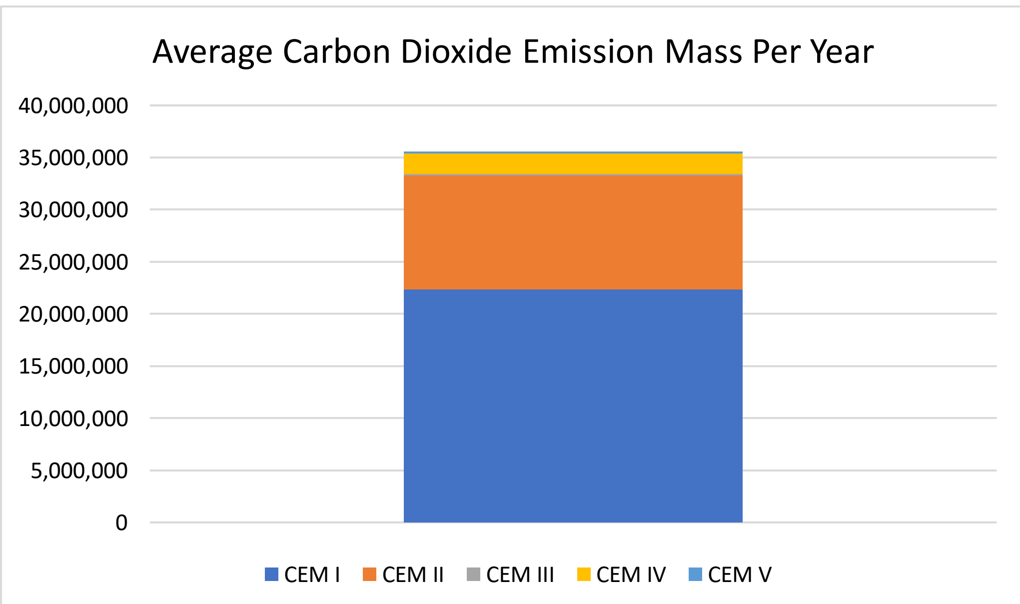
Cement Type	Average Carbon Dioxide Emission (metric tonnes)
CEM I	22,376,440
CEM II	10,895,884
CEM III	102,117
CEM IV	1,977,107
CEM V	195,829
Total	35,547,377

Summing up the values for each type:

$$22376440 + 10895884 + 102117 + 1977107 + 195829 = 35{,}547{,}377$$

As a result of the calculations, a total carbon dioxide emission of 35,547,377 tonnes in emitted to the atmosphere on average each year. CEM I is responsible for 63% of this, whereas CEM III is only responsible of 0.3% of the carbon dioxide emission. This is represented in the graph below.

Graph 1 – Graph showing the average carbon dioxide emission mass per year



To have further insights on the carbon dioxide emissions, let us imagine a Turkey where CEM I was used instead of CEM III between the years 2012 and 2023. In this situation, the carbon dioxide emissions that would have been prevented would be like so: The hypothetical carbon dioxide emission would be calculated using the production mass of CEM I but the clinker percentage of CEM III. This way, we can calculate the average carbon dioxide emission if CEM III was used instead of CEM I. Subtracting this value from the actual value is going to give the carbon dioxide mass that would have been prevented from emitting.

$$Emission\ That\ Would\ Have\ Prevented = Actual\ Emission - Hypothetical\ emission$$

Calculating the hypothetical value:

$$40{,}765{,}560 \times \frac{27.38}{100} = 11{,}161{,}610$$

$$11{,}161{,}610 \times 0.563 = 6{,}283{,}986$$

Actual average emission for CEM I was found to be 22,376,440 tonnes in Table 7. Subtracting the hypothetical value -6,283,763 tonnes- from this, results in 16,092,677.

$$Emission\ That\ Would\ Have\ Prevented = 22{,}376{,}440 - 6{,}283{,}986$$

$$= 16{,}092{,}454\ tonnes$$

We can take this a step further and calculate the emission that would have prevented if every cement type was replaced with CEM III. Repeating the calculations done above for each single cement type we get the following result. If each cement type was replaced with CEM III, 9,732,872 tonnes of carbon dioxide would be emitted. Which means that we would have prevented 25,814,505 tonnes of carbon dioxide from emitting into atmosphere.

4.4 Statistical Analysis

Even though the difference between each type of cement is self-evident, a statistical test should be conducted in order to accept or reject the null hypothesis. For this reason, a single factor ANOVA test was done on the data on Table 7. Here are the results of the test:

Table 9 – Table showing the results for the single factor ANOVA test done on Table 7

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
CEM I	12	269597224	22466435.34	8.50972E+12
CEM II	12	126242243.3	10520186.94	1.57502E+12
CEM III	12	1225403.102	102116.9252	2661714726
CEM IV	12	24096302.63	2008025.219	36875995985
CEM V	12	2347750.063	195645.8386	3298981931

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	4.44462E+15	4	1.11116E+15	548.5786022	1.32761E-43	2.539688635
Within Groups	1.11403E+14	55	2.02552E+12			
Total	4.55602E+15	59				

5. Conclusion

This essay explored the difference in carbon dioxide emissions between different cement types and concluded that CEM III caused the lowest carbon dioxide emission with an average of 102,117 tonnes of carbon dioxide annually, and CEM I caused the highest carbon dioxide emission with 22,376,440 tonnes of carbon dioxide on average. A total of 35,547,377 tonnes of carbon dioxide is emitted every year on average in Turkey. (Table 8)

Looking at the results of the ANOVA test, shown on Table 9, it can be said that there is a statistical difference between the carbon dioxide emissions of different cement types. Considering the p-value, it is seen that the p-value is much lower than 0.05, therefore H_0 is rejected and H_1 is accepted.

In conclusion, this essay showed the difference in carbon dioxide emissions between different types of cement, ultimately answering the research question which was “To what extent do different types of cement production processes (CEM I, II, III, IV, and V) affect the mass of carbon dioxide emitted (metric tons) in the construction industry of Turkey between the years 2012 and 2023?” It was showed that CEM I had the highest and CEM III had the lowest effect on the environment. As a result, the initial aim, which was to find out how each cement types affected the carbon dioxide emissions, was reached.

6. Discussion

It is shown that a total of 35,547,377 tonnes carbon dioxide is emitted on average each year. CEM I causes 63% of the carbon dioxide emissions in Turkey with 22,376,440 tonnes each year, whereas CEM III causes just 0.3% of it with 102,117 tonnes. However, this should situation has to be discussed. The fact that CEM I causes so many emissions is not only related with the clinker percentage. The magnitude of sales play a huge role in this number. Notice that the average yearly production of CEM I is 40,765,560 tonnes while CEM III is 662,480. For this reason, let us consider a case where the production of each cement type is the same. In this case, we can comment solely on the clinker percentage, independent of the sales amount. Which will still end up with CEM I having the most mass of carbon dioxide emissions as it has the highest clinker percent.

When considering the carbon dioxide emissions, we should not only look at the total production, but also at the percentages. CEM I has both the highest mass of production and highest carbon dioxide emission percent. On the other hand, despite having the lowest carbon dioxide emission levels CEM III has also the lowest mass of production. This shows that the construction industry in Turkey has not fully transitioned to environmentally friendly cement production methods yet. The industry in Turkey can be said to be "conservative" in this context. It is clearly seen that the cement type which has high carbon emission levels is preferred over the one that has lower levels.

Another remarkable insight on this topic would be calculating the carbon dioxide emissions that we could have prevented if he had used CEM III instead of CEM I. This is an important comparison as CEM I is the cement type that produces the most carbon dioxide emissions and CEM III causes the least. For this reason, we should consider the case where CEM III is used instead of CEM I. Supposing that CEM III was used instead of CEM I, the production mass of 40,765,560 ton cement would only cause 6,283,986 tonnes of carbon dioxide emission. This means that a total of 16,092,454 tonnes of carbon dioxide would not be emitted into atmosphere, harming the environment less. Taking this a step further, if each cement type was replaced with CEM III, 9,732,872 tonnes of carbon dioxide would be emitted. Which means that we would have prevented 25,814,505 tonnes of carbon dioxide from emitting into atmosphere.

Additionally, comparing the results that is found with the values that "Turkish GHG Inventory Report" published, it can be said that the method, which was developed in this exploration, is somewhat accurate. Turkish GHG Inventory reported on April 2022, that the average carbon dioxide emissions due to lime production between the years 2012-2020 was 35,977,000 tonnes. [Turkish Greenhouse Gas Inventory, 2022] Comparing this to the value that I found, an error percentage of 1.2% is present between the two. This error calculation was calculated by finding the difference between experimental value and the published value, dividing it by the published value and then multiplying by 100.

$$Error\ percentage = \frac{\text{Published value} - \text{Experimental value}}{\text{Published value}} \times 100$$

$$Error\ percentage = \frac{35{,}977{,}000 - 35{,}547{,}377}{35{,}977{,}000} \times 100$$

$$Error\ percentage = 1.2\%$$

7. Applications

The results of this exploration could be interpreted and applied in ways so that we can improve our lives, decrease our carbon emissions and crucially achieve the Sustainable Development Goals for a greener future.

7.1 What Could Be Done to Mitigate Carbon Dioxide Emissions?

To prevent the situation from going worse in the future, we should take action to mitigate our carbon dioxide emissions to the environment. There are various ways available that we can do to do so. Some of which are still being in the development process, and some of which are applicable even today.

As this exploration showed, we should first consider increasing the use of CEM III instead of CEM I as it produces less carbon dioxide. In addition, governments and companies should promote the use of cement types that even have lower carbon emissions. Researches and developments in the industry should be supported in order to allow for more innovations to be made.

To meet the goals of the Paris Agreement and keep global temperature rise below 1.5°C, reducing emissions alone is not enough, we must also actively remove CO2 from the atmosphere. Carbon Capture, Use and Storage (CCUS) is one such technology that can play a crucial role in addressing climate change. This method involves three steps: Capturing the carbon dioxide, transporting it and permanently storing it deep underground. [Intergovernmental Panel on Climate Change, IPCC, 2005] Predictions by the Global Cement and Concrete Association show that carbon capture, use and storage, CCUS, could reduce carbon emissions by 36% which makes it the largest factor to reduce the cement industry's emissions. [World Economic Forum, 2024]

More economically developed countries (MEDCs) have been working on to mitigate their carbon dioxide emissions. For instance, "Heidelberg Materials" from Germany works on low carbon cement that incorporates SCMs instead of clinker and uses the CCUS method to decrease the carbon emissions. [Princeton University, 2020] Another example is a company named Solidia from the USA. Solidia produces cement by capturing carbon emissions from the kiln and incorporating them into a special mixture, which is then used to fill the gaps in previously made cement. Instead of using water, the material is cured in a carbon dioxide-rich environment, significantly cutting emissions by 70%. This method not only speeds up the curing process but also enhances the cement's durability and reduces energy consumption, making it a more efficient and cost-effective alternative. [Princeton University, 2020] As a result, many see green cement as the future of sustainable construction. Another company from the USA, "Brimstone", has developed a process to produce cement from carbon-free calcium silicate blocks. [World Economic Forum, 2024] These are just a few examples; with the help of explorations like this one, more are yet to come.

8. Evaluation

This exploration provided results for the research question to be answered. The design and procedure of the exploration had some strengths and limitations. The strengths were like so:

Strengths:

1. Using a chemical formula to calculate the carbon dioxide mass. The chemical formula for the clinker production process allowed for precise calculations.
2. Secondary data exploration. Since this exploration did not involve any actual laboratory experiments, rather online researching, made it easy to access data.
3. Error percentage of 1.2% when compared to the actual data published by Turkish GHG Inventory Report. An error percentage of 1.2% could be considered good in this context.

Limitations:

1. Assumption. Since I did not have a direct data regarding the cement production, I had to assume that every cement that is produced was sold. This decreased the accuracy of the results.
2. A wide range of clinker percentages. The wide range of clinker percent for each cement type makes the calculations less accurate and less precise.
3. Lack of data diversity. Using only one data source for the exploration decreases the accountability of the data.

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