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The Variations of Magnetic Susceptibility Values in Raw Mix I during the Cement Production Process

Karin Yulfiarti[1], Hamdi Rifai[1], Fatni Mufid[1], Ahmad Fauzi[1], Ella Destari Ningsih[1], Ika Evy Wiyana[2], Fauzan[2]
[1]Universitas Negeri Padang, Indonesia
[2]PT. Semen Padang, Indonesia
karinyulfiarti@gmail.com *

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Abstract

Cement is an essential material widely used in construction, including bridges and buildings. The main raw materials for cement production consist of limestone (CaO) (±80%), silica sand (SiO_2) (±10%), clay (Al_2O_3) (±8%), and iron sand (Fe_2O_3) (±2%). During the cement production process, homogenization and quality control of raw materials occur at the Raw Mix I stage. However, current quality control systems generally do not consider magnetic mineral standards, even though iron sand as one of the raw materials contains magnetic minerals. Therefore, this study aims to analyze the variation of magnetic susceptibility values in Raw Mix I during the cement production process. A quantitative research design was employed, using a descriptive-analytical approach. Samples were collected hourly and measured using a Bartington Magnetic Susceptibility Meter MS2B at two different frequencies to obtain magnetic susceptibility and frequency-dependent susceptibility ($\chi FD\%$). The data were analyzed statistically by calculating the mean and standard deviation. The results show that the magnetic susceptibility values of Raw Mix I range from 102.87×10^{-8} m^3/kg to 165.93×10^{-8} m^3/kg, with an average value of $\chi = (134.4 \pm (3 \times 31.53)) \times 10^{-8}$ m^3/kg. Meanwhile, $\chi FD\%$ ranges from 0–2.9%, indicating a very low content of superparamagnetic grains. These findings provide additional information on magnetic mineral characteristics and may support improved quality control in cement raw material processing.

INTRODUCTION

Cement is one of the most important materials for human activities. National cement consumption has increased annually. The Indonesian Cement Association (ASI) reported that national cement consumption during January–February 2013 reached 9.04 million tons. Cement is a highly useful material for various construction purposes, such as bridges, buildings, and other infrastructures. The materials used in cement production consist of raw materials and additives. The main raw materials include limestone (CaO) (±80%), silica sand (SiO_2) (±10%), clay (Al_2O_3) (±8%), and iron sand (Fe_2O_3) (±2%). Meanwhile, the additives consist of

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gypsum ($CaSO_4 \cdot 2H_2O$), pozzolan, and high-grade limestone (Ikumapayi et al., 2025; Zhunusova et al., 2025). These materials react to form chemical compounds that function as binding agents. This consumption level represented an increase of about 11.3% compared with the same period in the previous year (2012), which was 8.12 million tons. Currently, cement is widely considered one of the essential materials in the development sector. The level of cement consumption is influenced by the growth of the property sector, including the construction of buildings, housing, and infrastructure projects planned by the government, such as bridges and other public facilities.

PT Semen X is one of the cement producers located in West Sumatra, with a production capacity of approximately 6,500,000 tons per year. The raw materials used in the cement production process include limestone, silica stone, clay, and iron sand with specific compositions. These materials are ground in the Raw Mill to produce a raw mix, which is then processed in a silo. After the raw mix is formed, it is transferred to the kiln system for further processing, including calcination and sintering at temperatures of approximately 1450°C, followed by quenching in a cooler until the temperature reaches around 100°C, resulting in the formation of clinker (Sharma et al., 2022). Clinker is a semi-finished product in cement production that is obtained through the burning of raw materials at high temperatures. The clinker produced is then ground in a cement mill. The cement mill is the final grinding equipment where clinker, gypsum, and additional materials (limestone and pozzolan) are processed to produce cement ready for distribution.

Magnetic mineral measurements can be conducted using a Bartington Magnetic Susceptibility Meter (MS2B), which has relatively high sensitivity and is easy to operate. Magnetic susceptibility is a measurement parameter that describes the magnetization properties of a material (Hariyanto et al., 2024). However, in cement production, measurements of magnetic minerals are generally not conducted based solely on magnetic susceptibility testing.

Cement production generally follows three major standards: the American Society for Testing and Materials (ASTM), the Indonesian National Standard (SNI), and the British Standard European Norm (BSEN), each of which includes chemical and physical parameters. These standards are applied to ensure cement quality through quality control and quality assurance processes. Quality testing in cement production is generally divided into Quality Assurance (QA) and Quality Control (QC), which monitor the production process from the initial stage until the final cement product. Quality Assurance includes testing using parameters such as X-ray analysis, H_2O content, particle size, sieve analysis (45 μm, 90 μm, 180 μm), temperature, liter weight, loss on ignition (LOI), false set, sieve residue, and ash content. Meanwhile, Quality Control includes tests such as X-ray analysis, H_2O content, free water, total moisture, inherent moisture, ash content, fixed carbon, calorific value, total sulfur, sieve analysis, chemical analysis, complete physical analysis, application tests, combined water, R_2O_3, CaO, MgO, SO_3, NaCl, total P_2O_3, and P_2O_3. However, among the existing quality control and quality assurance systems in cement production, none specifically considers magnetic mineral standards, even though one of the main raw materials used in cement production, iron sand, contains magnetic minerals.

Based on this condition, a magnetic susceptibility analysis was conducted on the cement raw material Raw Mix I at PT Semen X using the Bartington Magnetic Susceptibility Meter type MS2B. The MS2B is an instrument commonly used to determine the magnetic properties of a material and to estimate the abundance of magnetic minerals within a sample (Soomro et al., 2023; Sutter & Hooton, 2023). The cement production process at PT Semen X is illustrated in figure 1.

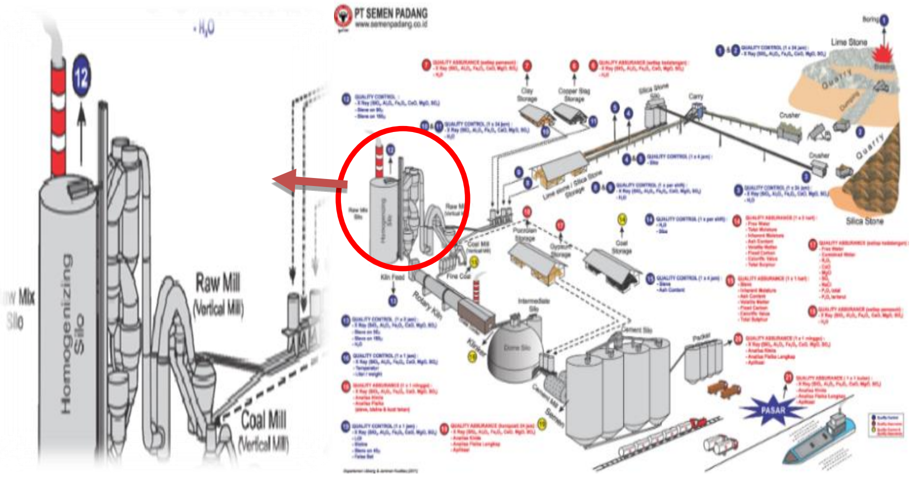

Fig 1. Grinding process of main ingredients for row mix i cement production

Based on Figure 1, the cement production process begins with raw materials of specific compositions that are ground in the Raw Mill to produce a raw mix, which is subsequently stored and processed in a silo. After the raw mix is formed, it is transferred to the kiln system for further processing, including calcination, sintering, and clinker formation. The clinker produced is then ground in the cement mill. The cement mill represents the final grinding stage, where clinker is processed together with gypsum and additional materials (limestone and pozzolan) to produce cement ready for distribution.

The Raw Mill is one of the main pieces of equipment used to grind raw materials into fine particles to form Raw Mix. At each stage of the production process, Quality Control (QC) and Quality Assurance (QA) tests are conducted, starting from the mining of raw materials, grinding, burning, clinker formation, and finally cement production at PT Semen X. The cement manufacturing process begins with raw materials that are crushed and ground in the Raw Mill under dry conditions until fine particles are produced. The resulting material is then calcined in a rotary kiln. In Raw Mill I, a homogenization system is applied, where the grinding and mixing processes are carried out under dry conditions, with a moisture content of approximately ±1% before entering the rotary kiln.

The objective of this study is to analyze the variation in magnetic mineral content in cement raw materials. Magnetic susceptibility is one of the magnetic parameters used to describe the ability of a material to become magnetized when an external magnetic field is applied.

METHODS

Sampling was conducted at PT Semen X (Figure 2) in accordance with the established sampling procedures, beginning with the determination of the sampling location followed by the collection of samples. Samples were collected every hour during working hours, resulting in approximately 4–13 samples per day. The variation in the number of samples was due to time limitations during sampling and technical constraints, such as equipment malfunction (Almquist et al., 2019; Gerring, 2017; Mohajan, 2020; Purssell & McCrae, 2020). The collected samples were placed in plastic bags and stored at the Geophysics Laboratory, Department of Physics, Faculty of Mathematics and Natural Sciences, Universitas Negeri Padang, for further analysis.

This study employed a quantitative research design with a descriptive-analytical approach, aiming to measure and statistically analyze the magnetic susceptibility of cement raw materials (Apuke, 2017; Purssell & McCrae, 2020; Sürücü & Maslakçi, 2020; Weyant, 2022). The research consisted of several stages, including research preparation, sample collection, ssample preparation, measurement, and data processing, carried out from November 2021 to February 2022.

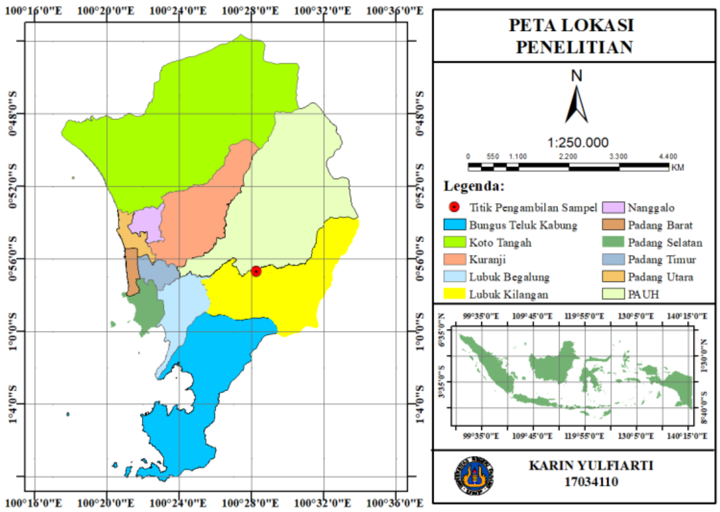

Fig 2. Location map of the research site at PT Semen X, West Sumatra, Indonesia

The next stage involved sample preparation. The rock samples were first ground using a mortar until fine particles were obtained. The prepared samples were then placed into sample containers and labeled to facilitate identification. The labeling system used the code RX1 010122 (9), where RX1 indicates the Raw Mix I sample, 010122 represents the sampling date (day, month, and year), and the number 9 indicates the sampling time.

Subsequently, the mass of each sample was measured using a digital balance prior to the magnetic susceptibility measurement. This weighing process was conducted to obtain the sample mass used as a reference during the susceptibility measurement process. The measurement procedure for determining the magnetic susceptibility values of Raw Mix I samples from PT Semen X is illustrated in Figure 3.

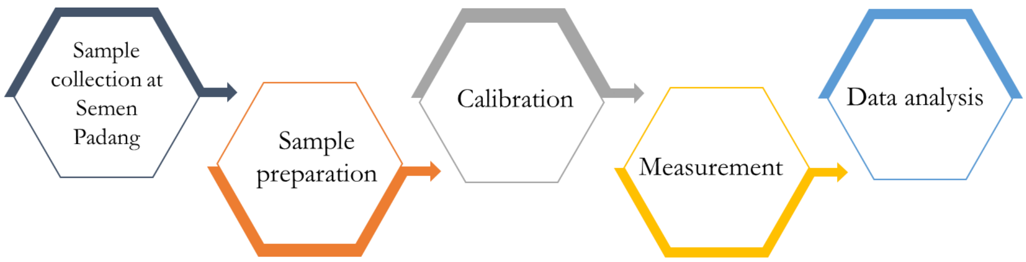

Fig 3. Flowchart of magnetic susceptibility analysis of Raw Mix I

After the calibration process, each sample was measured three times at low frequency and three times at high frequency to obtain the average magnetic susceptibility value. The comparison between measurements at the two frequencies was used to determine the frequency-dependent susceptibility (χFD%). Magnetic susceptibility measurements were carried out by magnetizing the samples using an external magnetic field at two frequency categories, namely low frequency (LF) and high frequency (HF). The magnetic susceptibility values displayed on the instrument screen were recorded and compiled in Microsoft Excel for further data processing.

The final stage involved data analysis. Samples consisting of cement production materials including clay, limestone, silica, iron sand, gypsum, pozzolan, high-grade limestone, clinker, and cement were measured for their magnetic susceptibility using a Bartington Magnetic Susceptibility Meter type MS2B. These measurements produced values of low-frequency susceptibility (χLF), high-frequency susceptibility (χHF), and frequency-dependent susceptibility (χFD%). The measurement data were then processed and plotted using Microsoft Excel to generate graphs illustrating the differences in the magnetic mineral response between low- and high-frequency susceptibility. The conceptual framework describing the influence of magnetic minerals on cement quality is presented in Figure 4.

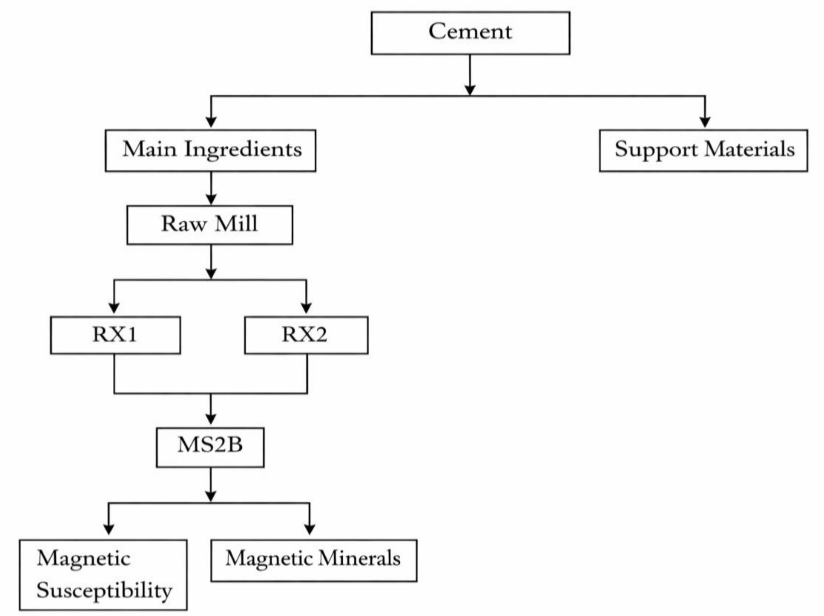

Fig 4. Research framework illustrating the influence of magnetic minerals on cement quality

Based on the results of the data analysis, the maximum and minimum magnetic susceptibility values were identified. The average magnetic susceptibility values were then calculated for each parameter, including low-frequency susceptibility (χLF), high-frequency susceptibility (χHF), susceptibility difference ($\Delta\chi$), and frequency-dependent susceptibility percentage (χFD%). The results of these calculations are presented in Table 2.

The magnetic susceptibility values (χ) were subsequently classified according to the criteria proposed by Hunt (1995) to determine the magnetic properties and the types of magnetic minerals contained in the cement raw materials. Meanwhile, the frequency-dependent susceptibility values (χFD%) were classified based on Dearing (1996) to estimate the grain size of magnetic minerals present in the samples. In addition, the magnetic susceptibility values and their standard deviations were calculated to determine the degree of data dispersion. The standard deviation was calculated using the standard formula, where $\bar{x}$ represents the mean value, xi represents the ith data value, and n represents the number of analyzed data points (Chi et al., 2023).

RESULT AND DISCUSSION

Magnetic susceptibility measurements were conducted at the Geophysics Laboratory, Universitas Negeri Padang, using a Bartington Magnetic Susceptibility Meter equipped with an MS2B sensor. The MS2B sensor was used to measure magnetic susceptibility values based on the mass of the sample. The samples consisted of Raw Mix I materials obtained from the homogenization process in Raw Mill I. A total of 62 samples were analyzed, with sampling conducted from 1 February to 15 February 2022.

The obtained data were then analyzed based on time intervals, namely daily, weekly, and the overall observation period, in order to evaluate the consistency of magnetic susceptibility values during the production process. Sample mass is one of the important parameters in the calculation of magnetic susceptibility values. Magnetic susceptibility measurements were carried out using the Bartington Magnetic Susceptibility Meter type MS2B, and the resulting data were processed to obtain the maximum, minimum, and average magnetic susceptibility values. The magnetic susceptibility values for the period 1 February to 15 February 2022 are presented in Table 1.

Table 1. Magnetic susceptibility values (χLF, χHF, Δχ, and χFD%) of Raw Mix I samples at PT Semen X

Sample Name	Parameter	Max	Min	Average
RX1 010222	χLF	149.7	113.7	126.9
	χHF	147.6	112	125.8
	χFD	0.015	0.00	0.009
	χFD (%)	1.5	0.00	0.882
RX1 070222	χLF	125.2	84.2	111.2
	χHF	123.4	82.2	109.9
	χFD	0.024	0.025	0.013
	χFD (%)	2.38	0.25	1.262
RX1 090222	χLF	165.9	118.6	139.6
	χHF	164.8	117.8	141.5
	χFD	0.027	0.006	0.013
	χFD (%)	2.67	0.61	1.31
RX1 100222	χLF	168.5	95.4	140.9
	χHF	166.7	94.4	139.8
	χFD	0.016	0.000	0.008
	χFD (%)	1.60	0.00	0.77
RX1 110222	χLF	148.5	83.3	131.0
	χHF	145.2	82.6	129.6
	χFD	0.022	0.003	0.011
	χFD (%)	2.22	0.28	1.05
RX1 140222	χLF	167.7	84.1	124.08

	χHF	167.6	83.9	120.2
	χFD	0.021	0.001	0.008
	χFD (%)	2.08	0.06	0.81
RX1 150222	χLF	273.5	98.3	142.0
	χHF	272.0	96.8	140.7
	χFD	0.015	0.000	0.008
	χFD (%)	1.52	0	0.81

Based on Table 1, the measurements of the raw cement samples (RX1) were conducted under low-frequency susceptibility (χLF) and high-frequency susceptibility (χHF) conditions, as well as frequency-dependent susceptibility (χFD%). The measurement results obtained during seven days of observation (1–15 February 2022) indicate variations in magnetic susceptibility values in the Raw Mix I samples. The highest magnetic susceptibility value was observed in sample RX1 150222, with a value of 273.5 × 10^{-8} m^3/kg, whereas the lowest value was recorded in sample RX1 070222, with a value of 125.2 × 10^{-8} m^3/kg.

The highest high-frequency susceptibility (χHF) value was also observed in sample RX1 150222, with a value of 272.0 × 10^{-8} m^3/kg, while the lowest value occurred in sample RX1 070222, with 123.4 × 10^{-8} m^3/kg. The minimum, maximum, and average magnetic susceptibility values during the period 1 February to 15 February 2022 are presented in Figure 5.

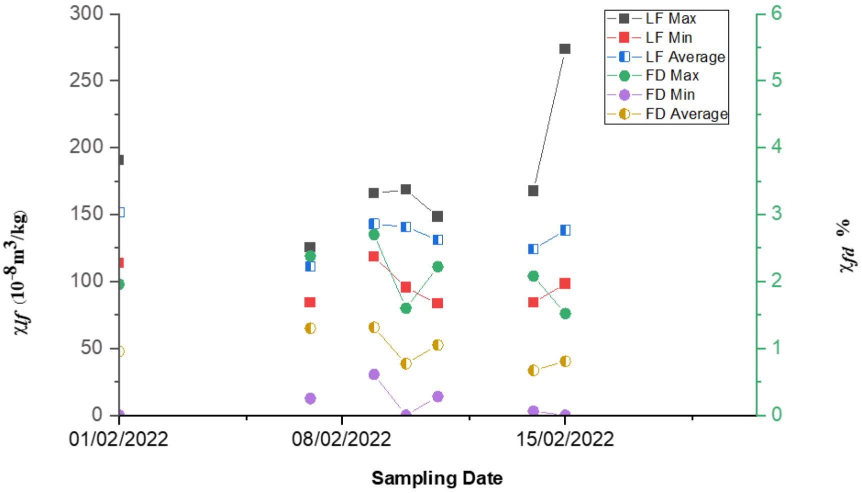

Fig 5. Minimum, maximum, and average magnetic susceptibility (χ) values of Raw Mix I samples

Based on Figure 5, the low-frequency magnetic susceptibility (χLF) values measured per hour are not significantly different from the high-frequency magnetic susceptibility (χHF) values. The highest χHF value was observed in sample RX1 150222 (15) with a value of 272 × 10^{-8} m^3/kg, whereas the lowest χHF value was recorded in sample RX1 070222 (14) with a value of 82.2 × 10^{-8} m^3/kg. Meanwhile, the highest low-frequency susceptibility (χLF) value was also observed in sample RX1 150222 (15) with a value of 273.5 × 10^{-8} m^3/kg, while the lowest value occurred in sample RX1 110222 (15) with 83.3 × 10^{-8} m^3/kg.

The weekly average values of low-frequency susceptibility (χLF) at PT Semen X show variations that may indicate the consistency of magnetic susceptibility values during each week of observation. The highest weekly average was obtained in the fourth week of February 2022, with a value of 163.0 × 10^{-8} m^3/kg, while the lowest average occurred in the first week of February 2022, with a value of 131.4 ×

10^{-8} m³/kg. Therefore, the weekly average low-field susceptibility (χLF) ranged from 131.4 × 10^{-8} m³/kg to 163.0 × 10^{-8} m³/kg.

Low magnetic susceptibility values may be associated with weathering and deposition processes mixed with diamagnetic organic materials (Aubineau et al., 2024). In contrast, higher magnetic susceptibility values may indicate the presence of magnetic minerals within the samples, which could be influenced by mineral transport processes through water or wind (Hamdan et al., 2022). Therefore, the presence of magnetic minerals in iron sand samples may be evaluated through the analysis of their magnetic susceptibility values.

Furthermore, the obtained magnetic susceptibility values were classified according to the criteria proposed by Hunt (1995) to determine the magnetic properties of the Raw Mix I samples at PT Semen X. Variations in magnetic susceptibility values may occur because the raw materials used in cement production originate from different locations, which may be influenced by varying environmental and geological conditions. In general, rock magnetization exhibits anisotropic behavior, meaning that magnetic susceptibility values may vary when a magnetic field is applied in different directions (Venkateshwarlu et al., 2022). A rock sample is considered magnetically anisotropic when its magnetic properties depend on the direction of measurement. Therefore, the identification of magnetic minerals contained in the Raw Mix I samples can be conducted through the analysis of their magnetic susceptibility values (Ayoubi et al., 2019).

Minerals are naturally occurring compounds formed through geological processes and consist of chemical elements arranged in an ordered atomic structure (Krivovichev et al., 2020). Minerals also represent the primary constituents of rocks, characterized by specific properties such as crystal form and chemical composition (Krivovichev et al., 2022). In general, minerals exhibit five main magnetic properties, namely diamagnetic, paramagnetic, ferromagnetic, antiferromagnetic, and ferrimagnetic behaviors (Wang, 2025). The magnetic properties of the samples are presented in Table 2.

Table 2. Magnetic properties of Raw Mix I samples at PT Semen X

Sample Name	Magnetic Susceptibility Value (x 10^{-8} m^3/kg)	Magnetic Properties
RX1 010222	113.7-149.7	*Antiferromagnetic*
RX1 070222	84.2-125.2	*Antiferromagnetic*
RX1 090222	118.6-165.9	*Antiferromagnetic*
RX1 100222	95.4-168.5	*Antiferromagnetic*
RX1 110222	83.3-148.5	*Antiferromagnetic*
RX1 140222	84.1-167.7	*Antiferromagnetic*
RX1 150222	98.3-273.5	*Antiferromagnetic*

Based on Table 2, magnetic minerals classified as ferromagnetic minerals are generally referred to as magnetic minerals. The results indicate that the Raw Mix I samples at PT Semen X do not contain superparamagnetic grains, as indicated by χFD% values lower than 2%. However, several samples exhibit χFD% values between 2% and 10%, suggesting the possible presence of a mixture of superparamagnetic and coarser magnetic grains.

Specifically, χFD% values ranging from 2.02–2.38% were observed in sample RX1 070222, 2.67% in sample RX1 090222, 2.22% in sample RX1 110222, 2.08% in sample RX1 140222, 2.01–2.82% in sample RX1 160222, 2.19–2.28% in sample

RX1 170222, 2.77% in sample RX1 180222, 2.22–2.90% in sample RX1 210222, and 2.01% in another measurement of sample RX1 210222.

These values suggest that the samples may contain a mixture of superparamagnetic particles and coarser magnetic grains (<0.05 μm). The relationship between low-frequency susceptibility (χLF) (10^{-8} m^3/kg) and χFD% is presented in Figure 6.

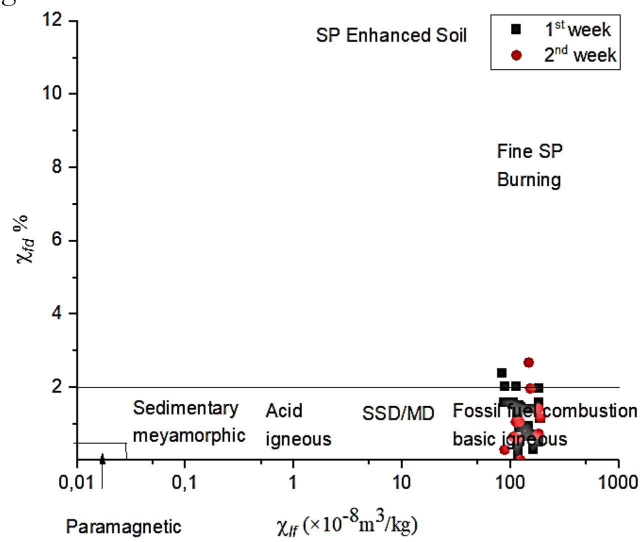

Fig 6. Relationship between low-frequency susceptibility (χLF) (10^{-8} m^3/kg) and frequency-dependent susceptibility (χFD%)

Figure 6 shows the relationship between low-frequency magnetic susceptibility (χLF) (10^{-8} m^3/kg) and frequency-dependent susceptibility (χFD%) for the Raw Mix I cement samples. The χFD% values obtained vary within the range of 0%–2.9%. The highest value was observed in sample RX1 210222 (16) with 2.9%, while the lowest frequency-dependent susceptibility value (0%) was observed in several samples, namely RX1 010222 (5), RX1 100222 (13), and RX1 150222 (12).

A rock sample is considered magnetically anisotropic when its magnetic properties depend on the direction of measurement (Sagnotti, 2021). Based on the graph, χFD% values within the range of 0–1.99% fall into the low field category (<2%), whereas values ranging from 2.01–2.9% fall into the moderate category (2–10%). Values of χFD% < 2% indicate that the magnetic minerals in the samples likely do not contain superparamagnetic grains, whereas values between 2% and 10% suggest that the magnetic minerals may contain a mixture of superparamagnetic particles and coarser grains (Oudeika et al., 2020). The standard deviation of magnetic susceptibility values is presented in Table 3.

Table 3. Standard deviation values of Raw Mix I (RX1) cement raw materials at Cement Plant X during 1–15 February 2022

Standard Deviation of Low Frequency Magnetic Susceptibility (χLF)				
Week	**Date**	**Daily Standard Deviation**	**Weekly Standard Deviation**	**Overall Standard Deviation**
First	February 1, 2022	28.14	30.07	31.53
	February 7, 2022	14.37		
Second	February 9, 2022	17.09	32.81	
	February 10, 2022	21.54		

	February 11, 2022	20.92		
	February 14, 2022	32.51		
	February 15, 2022	62.50		
Average		**28.15**	**31.44**	**31.53**

The results in Table 3 indicate that the standard deviation values of Raw Mix I samples at PT Semen X vary across the observation period. During the first week (1 and 7 February 2022), the weekly standard deviation was 30.07, while during the second week of February the standard deviation was 32.81. For the overall observation period from 1 February to 15 February 2022, the standard deviation value was 31.53. The standard deviation value reflects the degree of data dispersion around the mean value, and consistent values indicate that the data distribution is relatively close to the average value (Frery, 2023; McGrath et al., 2020; Sagnotti, 2021).

CONCLUSION

The analysis of magnetic susceptibility values of Raw Mix I cement materials at PT Semen X indicates that the susceptibility values vary within the range of 102.87×10^{-8} m³/kg to 165.93×10^{-8} m³/kg, with an average value of 134.4×10^{-8} m³/kg and a standard deviation of ±31.53. This variation suggests differences in the magnetic mineral content within the Raw Mix I samples during the observation period. Based on the obtained susceptibility range, the magnetic properties of the Raw Mix I materials are classified as antiferromagnetic. Furthermore, the relatively low values of frequency-dependent susceptibility ($\chi FD\%$) indicate that superparamagnetic grains are nearly absent in the analyzed samples. These findings provide insight into the magnetic mineral characteristics of Raw Mix I materials used in the cement production process at PT Semen X.

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DECLARATIONS

Author contribution

Karin Yulfiarti, Fatni Mufid: Writing-Preparation of original manuscript, **Ahmad Fauzi:** Conceptualization, Methodology, **Hamdi Rifai, Ella Destari Ningsih:** Visualization, Investigation, Improve Content, **Ika Evy Wiyana, Fauzan:** Data accuracy and analysis, Improve Language.

AI Statement

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Conflict of interest

The authors declare that this research was conducted without any conflict of interest in the research.

Ethical clearance

The research company has agreed to carry out the research and is willing if the results of this research are published.

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