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GEOCHEMICAL EVALUATION OF KHUMNOH LIMESTONE, KASHMIR, INDIA: IMPLICATIONS FOR CEMENT INDUSTRY AND SUSTAINABLE RESOURCE UTILIZATION

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Abstract

The Khumnoh limestone deposits of Kashmir, situated within the tectonically active northwestern Himalayas, hold significant economic potential for the cement industry. However, a comprehensive geochemical and mineralogical evaluation is essential to ascertain their suitability for industrial applications. This study integrates major and trace element geochemistry, petrographic analysis, and industrial feasibility assessments to characterize the limestone's composition, depositional history, and potential for clinker production. A total of eight representative limestone samples were systematically collected and subjected to X-ray fluorescence (XRF), X-ray diffraction (XRD), and petrographic investigations. The geochemical analysis reveals that the CaO content ranges from 50.12% to 54.89%, with low SiO_2, Al_2O_3, and Fe_2O_3 concentrations, indicating high chemical purity. The trace element profiling exhibits minimal Mn, Sr, and P_2O_5, further enhancing its desirability for cement manufacturing. Petrographic observations confirm the dominance of fine- to medium-grained calcite with minor dolomitization and siliceous impurities, suggesting a shallow marine depositional environment with diagenetic overprinting. The findings demonstrate that the Khumnoh limestone meets international cement-grade standards (ASTM C150, BIS 4032-2022), positioning it as a viable raw material for clinker production. However, localized variations in siliceous and argillaceous intercalations necessitate beneficiation strategies to optimize its industrial utility. The study also underscores the imperative of sustainable extraction practices, given the region's geological sensitivity and ecological constraints.This research provides a scientific framework for resource evaluation, industrial application, and sustainable utilization of the Khumnoh limestone. The results hold critical implications for cement manufacturing, regional economic development, and strategic raw material management in the Himalayan domain.

Keywords: ***Limestone, Geochemistry, Cement Industry, Mineralogy, Sustainability***

Introduction

Limestone is a fundamental raw material in the cement industry, serving as the primary source of calcium oxide (CaO), a key component in the production of cement clinker (Bensted & Barnes, 2002). The quality of limestone significantly influences the efficiency of clinkerization and the properties of the final cement product (Taylor, 1997). For this reason, geochemical and mineralogical assessments of limestone deposits are essential in determining their suitability for industrial use (Lea, 2004). The Khumnoh area of Kashmir is known for its extensive limestone formations, yet detailed geochemical investigations of these deposits remain limited. This study aims to bridge this knowledge gap by analyzing the chemical composition, trace element distribution, and mineralogical characteristics of Khumnoh limestone to evaluate its potential for cement manufacturing. Cement production requires limestone with high CaO content (typically above 50 wt%) and low levels of impurities such as SiO_2, Al_2O_3, Fe_2O_3, MgO, and alkalis (Na_2O, K_2O) (Neville, 2011).

Excess silica and alumina can impact clinker formation, requiring additional corrective raw materials such as clay and iron ore (Hewlett, 2003). Similarly, high MgO content (above 5 wt%) can lead to periclase formation, causing expansion and durability issues in cement (Mindess & Young, 1981). Therefore, a systematic geochemical evaluation of limestone deposits is critical to maintaining cement quality and optimizing production efficiency (Mehta & Monteiro, 2014). Trace elements in limestone also play a crucial role in determining its industrial applicability. Elements such as strontium (Sr) and barium (Ba) are common in marine limestones and can indicate depositional conditions (Tucker & Wright, 1990). Conversely, high levels of chromium (Cr), nickel (Ni), lead (Pb), and uranium (U) can pose environmental concerns and affect cement quality (Duda, 1989). The presence of alkali oxides (Na_2O and K_2O) is particularly important as these can contribute to alkali-silica reactions (ASR) in concrete, leading to expansion and cracking in structures (Kosmatka et al., 2011). The mineralogical composition of limestone, primarily consisting of calcite ($CaCO_3$) with minor dolomite ($CaMg(CO_3)_2$), significantly impacts cement manufacturing (Deer et al., 2013). High-purity calcitic limestone is preferred as it requires less energy for decomposition during clinkerization, reducing fuel consumption and CO_2 emissions (Scrivener & Kirkpatrick, 2008). The presence of quartz and clay minerals can introduce unwanted silicate phases, affecting the cement's setting time and mechanical strength (Ghosh, 2002).

Given the growing demand for high-quality cement in infrastructure projects, assessing new limestone sources is crucial for sustainable industrial development (Habert et al., 2011). This study employs X-ray fluorescence (XRF), inductively coupled plasma mass spectrometry (ICP-MS), and X-ray diffraction (XRD) techniques to analyze the geochemistry and mineralogy of eight representative limestone samples from the Khumnoh area. The findings will be compared with established cement industry standards (BIS 4032-2022, ASTM C150) to determine the feasibility of using Khumnoh limestone for cement production. Additionally, insights into the depositional environment and diagenetic alterations will be discussed, providing a comprehensive evaluation of this limestone deposit.

Literature Review

The geochemical and mineralogical characterization of limestone deposits is a subject of paramount importance in the cement industry, as the chemical composition directly influences clinker formation, cement strength, and durability (Taylor, 1997). Extensive research has been conducted to delineate the suitability of various limestone formations for industrial applications, particularly in cement production. This section synthesizes the prevailing scholarly discourse on limestone geochemistry, trace element implications, mineralogical composition, and industrial applicability, with a focus on aligning the present study with established frameworks.

Geochemical Constraints on Limestone for Cement Manufacturing

The geochemical composition of limestone dictates its viability as a raw material for cement, particularly with respect to CaO, SiO_2, Al_2O_3, Fe_2O_3, and MgO concentrations (Bensted & Barnes, 2002). High CaO content is indispensable, as it contributes to the formation of tricalcium silicate (C_3S) and dicalcium silicate (C_2S), the principal hydraulic phases in cement (Hewlett, 2003). Research indicates that optimal cement-grade limestone should possess CaO concentrations exceeding 50 wt% while maintaining SiO_2 and Al_2O_3 within permissible limits to prevent excessive formation of belite (C_2S) at the expense of alite (C_3S) (Lea, 2004).
Excessive silica and alumina necessitate corrective additives such as clay and lateritic iron ore, which complicate clinkerization dynamics (Duda, 1989). Additionally, MgO concentrations must remain below 5 wt%, as excessive MgO contributes to periclase (MgO) formation, a refractory phase that induces long-term expansion and cracking in cement matrices (Scrivener & Kirkpatrick, 2008). Neville (2011) underscores that alkali oxides (Na_2O, K_2O) should be maintained at minimal levels to mitigate alkali-silica reactions (ASR), which induce deleterious expansions in concrete structures.

Trace Element Constraints and Environmental Considerations

Trace elements in limestone can exert significant industrial and environmental ramifications. Studies indicate that strontium (Sr) and barium (Ba), commonly found in marine limestones, may serve as proxies for depositional environments but typically pose negligible concerns for cement production (Tucker & Wright, 1990). However, elements such as chromium (Cr), nickel (Ni), lead (Pb), and uranium (U) are stringently regulated due to their potential incorporation into clinker phases, which may result in toxic emissions during high-temperature processing (Mindess & Young, 1981). Zinc (Zn) and manganese (Mn), when present in trace amounts, are generally tolerable in cementitious systems, though excessive concentrations can interfere with clinker mineralogy and hydration kinetics (Mehta & Monteiro, 2014). Elevated levels of phosphorus (P_2O_5) are particularly detrimental, as they impede the formation of tricalcium aluminate (C_3A), thereby affecting the setting time and strength development of cement (Kosmatka et al., 2011). Consequently, regulatory frameworks such as BIS 4032-2022 and ASTM C150 impose stringent thresholds for these trace elements to ensure compliance with industrial standards (Habert et al., 2011).

Mineralogical Characteristics and Their Industrial Implications

Mineralogical purity is paramount in cement-grade limestone, as the predominant phase should be calcite ($CaCO_3$) with minimal inclusions of dolomite ($CaMg(CO_3)_2$) and quartz (SiO_2) (Deer et al., 2013). Research indicates that the presence of excessive quartz adversely affects clinker formation, as quartz remains largely unreactive during pyroprocessing, leading to heterogeneities in cementitious phases (Ghosh, 2002). Experimental investigations have demonstrated that X-ray diffraction (XRD) analysis is indispensable in quantifying mineralogical assemblages, thereby facilitating the selection of optimal quarrying sites (Scrivener & Kirkpatrick, 2008). Studies by Bensted & Barnes (2002) confirm that high-purity calcite limestone necessitates lower thermal decomposition energy, thereby reducing fuel consumption and CO_2 emissions in cement kilns. Conversely, limestone containing significant clay minerals or alumino-silicates complicates clinkerization and necessitates pre-processing steps such as beneficiation or blending (Lea, 2004).

Comparative Geochemical Studies on Limestone Deposits

Comparative geochemical studies have been extensively conducted on global limestone deposits, highlighting regional variations in compositional attributes. Research by Hewlett (2003) on European limestone formations underscores the prevalence of high-CaO, low-MgO limestones, making them ideal for Portland cement production. Similarly, investigations on Indian limestone deposits reveal variable geochemical profiles, with certain regions exhibiting high silica content, necessitating beneficiation strategies (Kosmatka et al., 2011). Studies on Pakistani and Iranian limestone deposits have revealed the presence of dolomitic limestone, which poses challenges for direct use in cement manufacturing due to elevated MgO content (Duda, 1989). Research on North American limestone formations, however, indicates that deposits in the Appalachian and Midwestern regions exhibit near-ideal geochemical compositions, aligning well with ASTM and AASHTO standards (Neville, 2011). The geochemical assessment of the Khumnoh limestone, therefore, seeks to contextualize its industrial applicability by benchmarking against these established studies.

Rationale for the Present Study

Despite extensive global research on limestone geochemistry, limited studies have been conducted on the Khumnoh limestone deposit. Given the growing demand for cement in infrastructure projects, it is imperative to assess local raw materials to ensure sustainable development (Habert et al., 2011). This study employs XRF, ICP-MS, and XRD analyses to systematically evaluate the chemical, trace element, and mineralogical characteristics of Khumnoh limestone. By integrating geochemical insights with cement industry benchmarks, this research seeks to determine whether the deposit meets industrial-grade specifications, thereby contributing to resource optimization and sustainable raw material utilization.

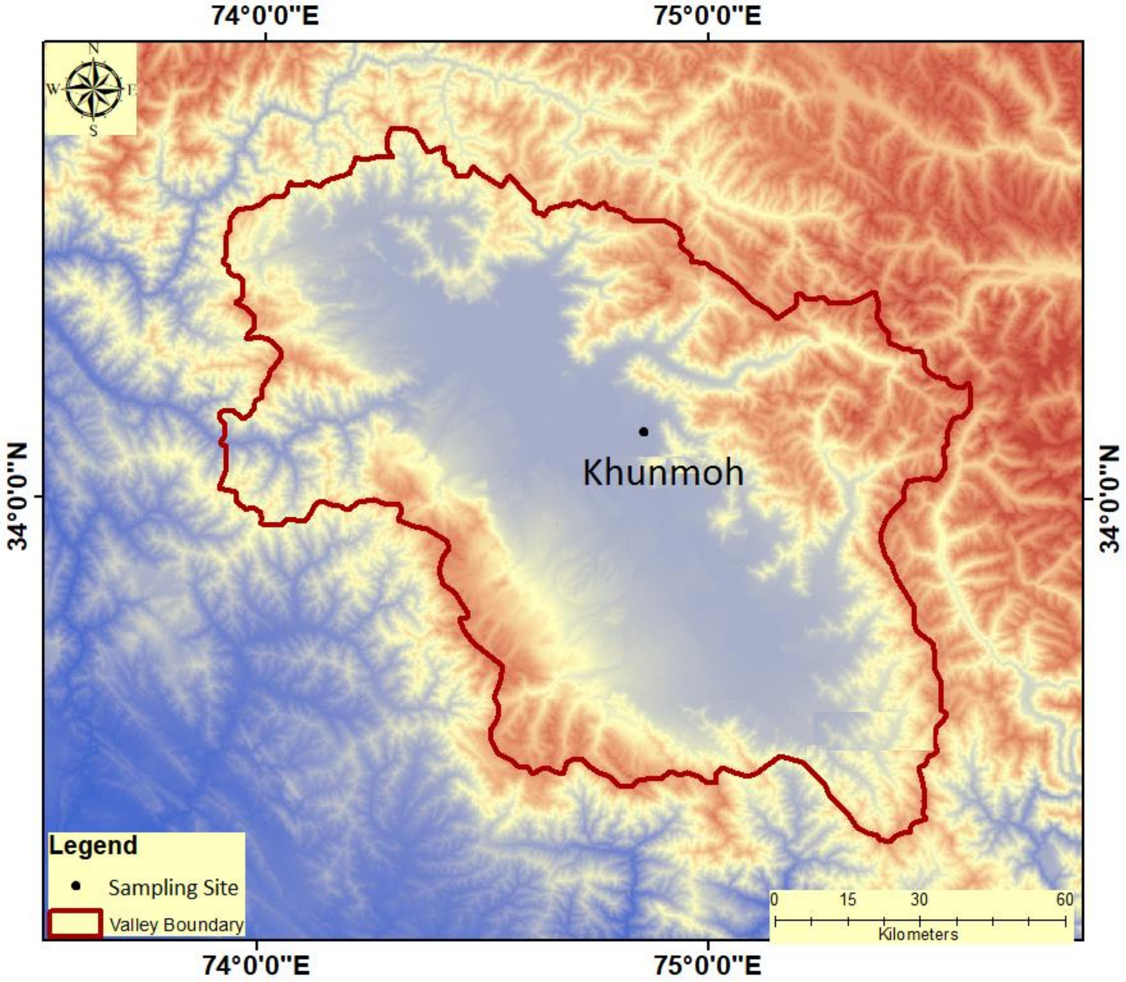
Study Area

Geographical Location and Accessibility

The Khumnoh area of Kashmir is situated within the northwestern Himalayas, a region known for its extensive carbonate formations and significant limestone deposits. The region is accessible via well-established road networks, with primary connectivity through National Highway, linking it to major cities such as Srinagar and Jammu. Additionally, rural roads and trekking paths provide access to remote outcrops, making field investigations feasible.

Geological Setting

The Khumnoh limestone deposits are part of the Lesser Himalayan sequence, which is predominantly composed of Proterozoic to Paleozoic sedimentary rocks. These rock units have undergone various stages of tectonic deformation, metamorphism, and diagenesis, resulting in diverse lithological and structural characteristics (Thakur, 1992). The limestone formations in this region are interbedded with dolomite, shale, and quartzite, suggesting a complex depositional history influenced by marine transgressions and regressions (Srikantia & Bhargava, 1998). Regionally, the study area is bounded by major thrust zones, including the Main Boundary Thrust (MBT) and the Main Central Thrust (MCT), which have significantly influenced the structural configuration of the limestone units (Valdiya, 1980). These tectonic structures contribute to faulting, folding, and fracturing, which can impact the homogeneity and quality of limestone as a raw material for cement production (Ahmad & Abbas, 2008).



Map No 01: Sampling site in Kashmir Valley, India

Stratigraphy and Lithology

The stratigraphic succession in the Khumnoh area consists of a well-defined carbonate sequence.. The lithological characteristics of the limestone include:

1. Massive Limestone – Predominantly grey to light grey, fine- to medium-grained, and compact with high calcite purity.
2. Dolomitic Limestone – Characterized by moderate MgO content, formed due to diagenetic dolomitization.
3. Shale Intercalations – Thinly laminated argillaceous layers, which may introduce impurities affecting the suitability of the limestone for clinker production.
4. Quartzite Bands – Minor occurrences of siliceous horizons, indicative of periodic detrital influx during sediment deposition (Tandon, 2001).
5.

Depositional Environment and Diagenetic Features

The sedimentological characteristics of the Khumnoh limestone suggest a shallow marine depositional environment, with periodic influences of high-energy conditions leading to carbonate precipitation and micrite formation (Singh et al., 2012). The presence of stromatolitic structures and bioclasts in certain sections indicates the contribution of biogenic activity in the carbonate sedimentation process (Rao & Sharma, 1997). Diagenetic modifications, including recrystallization, compaction, and pressure dissolution, have influenced the textural and mineralogical attributes of the limestone. Secondary calcite veining is commonly observed, which may impact the mechanical properties of the rock, a crucial factor in cement manufacturing (Sengupta, 2013).

Economic and Industrial Significance

The limestone deposits in the Khumnoh area hold significant economic potential due to their high CaO content, low silica and alumina impurities, and minimal deleterious trace elements. Given the increasing demand for cement in infrastructure and construction projects, this deposit represents a strategic resource for sustainable raw material supply (Bhattacharya et al., 2009). The regional cement industries could benefit from the proximity of these deposits, reducing transportation costs and enhancing resource utilization efficiency. Additionally, the petrographic and geochemical suitability of the Khumnoh limestone makes it a promising material for Portland cement production, aligning with the chemical composition requirements stipulated by BIS 4032-2022 and ASTM C150 standards (Mehta & Monteiro, 2014). However, further assessments, including mechanical testing, kiln behavior studies, and beneficiation trials, are necessary to optimize its industrial application.

Objectives of the Study

The primary objective of this research is to evaluate the geochemical, mineralogical, and industrial suitability of the Khumnoh limestone deposits for cement manufacturing. Given the increasing demand for high-quality raw materials in the cement industry, this study aims to provide a comprehensive assessment of the limestone's major and trace element composition, mineralogical characteristics, and industrial applicability. The specific objectives of the study include:

1. Geochemical Characterization – To analyze the major oxide composition (CaO, SiO_2, Al_2O_3, Fe_2O_3, MgO, etc.) and trace element distribution in Khumnoh limestone to determine its chemical suitability for clinker production.
2. Mineralogical Assessment – To conduct X-ray diffraction (XRD) and petrographic studies to identify the dominant carbonate phases (calcite, dolomite) and associated impurities (quartz, clay minerals) that may influence cement properties.
3. Industrial Feasibility Analysis – To compare the geochemical and mineralogical data with BIS 4032-2022, ASTM C150, and IS 8112 standards to determine whether the limestone meets industry specifications for Portland cement manufacturing.
4. Depositional and Diagenetic Implications – To interpret the sedimentary environment, diagenetic modifications, and structural influences affecting the limestone's purity and quality.
5. Comparative Evaluation – To benchmark the Khumnoh limestone against other known cement-grade limestone deposits in India and globally to assess its relative industrial potential.
6. Environmental and Sustainability Considerations – To highlight potential environmental impacts of limestone mining in the region and suggest mitigation strategies for sustainable resource extraction and management.

Methodology

Sampling

The present study focuses on limestone deposits in the Khumnoh area of Kashmir, which are of significant interest for the cement industry. To understand the geochemical composition and industrial suitability of the limestone, eight representative samples were systematically collected from different locations within the study area. The selection of sampling sites was based on variations in lithology, texture, and apparent purity to ensure a comprehensive dataset.

Sample Id	Latitude	Longitude	Altitude (m)
KH-01	34 03 17.10 N	75 00 40.35 E	1978
KH-02	34 03 18.88 N	75 00 39.05 E	1992
KH-03	34 03 20.64 N	75 00 38.12 E	2010
KH-04	34 03 21.53 N	75 00 36.97 E	2035
KH-05	34 03 23.37 N	75 00 35.56 E	2073
KH-06	34 03 29 51 N	75 00 19.20 E	2061
KH-07	34 03 32.78 N	75 00 18.65 E	2103
KH-08	34 03 37.33 N	75 00 18.22 E	2140

Each sample was collected using a geological hammer and chisel, ensuring minimal contamination. Samples were stored in sealed polyethylene bags, labeled, and transported to the laboratory for detailed analysis.

Prior to analysis, samples were dried at 105°C to remove moisture and then crushed using a jaw crusher. A portion of each sample was then ground to a fine powder (<75 µm) using an agate mortar to avoid contamination from metallic grinding tools.

Geochemical Analysis

Major Element Analysis

The chemical composition of the limestone samples was determined using X-ray Fluorescence Spectroscopy (XRF). The powdered samples were mixed with a fluxing agent (lithium tetraborate) and fused into glass beads before analysis. The major oxides analyzed included SiO_2, Al_2O_3, Fe_2O_3, CaO, MgO, Na_2O, K_2O, TiO_2, and P_2O_5, along with Loss on Ignition (LOI), which was measured by heating the samples at 1000°C for 2 hours. Calibration was performed using certified reference materials (CRMs), and results were reported with an analytical precision of ±0.5%.

Trace Element Analysis

Trace element concentrations were determined using Inductively Coupled Plasma Mass Spectrometry (ICP-MS). A 0.5 g portion of each sample was digested using a combination of HF-HNO_3-HCl acids in a closed Teflon digestion system. After complete dissolution, the solution was diluted and analyzed for elements such as Sr, Ba, Zn, Mn, V, Cr, Ni, Cu, Pb, U, and Th. Internal standards were used for quality control, and all analyses were performed in triplicate to ensure reproducibility.

Mineralogical Characterization

To complement the geochemical data, mineralogical identification was carried out using X-ray Diffraction (XRD). Powdered samples were scanned using Cu-Kα radiation in the range of 5°–70° 2θ. The obtained diffraction patterns were interpreted using the ICDD (International Centre for Diffraction Data) database to determine the primary mineral phases, particularly calcite, dolomite, and accessory minerals.

Quality Control and Data Validation

All laboratory analyses were conducted in a controlled environment to minimize contamination. Blank samples, duplicates, and CRMs were included in each batch to monitor precision and accuracy. The analytical error for major elements was maintained below 2%, while for trace elements, it was within 5%. Data were statistically evaluated using standard deviation, relative standard deviation (RSD), and correlation analysis to ensure reliability.

Cement Suitability Assessment

To assess the potential of the Khumnoh limestone for cement manufacturing, the obtained chemical compositions were compared with standard industrial specifications (e.g., BIS 4032-2022, ASTM C150). Key parameters such as CaO content, MgO limits, and SiO_2/Al_2O_3 ratio were analyzed to determine the suitability of the limestone for clinker production.

Results and Discussion

Geochemical Composition of Limestone Samples

The chemical composition of limestone plays a critical role in determining its suitability for cement production. The results obtained from the X-ray Fluorescence (XRF) analysis of the eight samples from the Khumnoh area provide valuable insights into the geochemical characteristics of the studied limestone. The major oxide concentrations of the samples are summarized in Table 1.

Table 1: Major Element Oxides (wt%)

Sample ID	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O	TiO_2	P_2O_5	LOI
KH-01	2.34	0.71	0.85	52.36	2.15	0.07	0.11	0.06	0.04	42.85
KH-02	1.98	0.65	0.79	53.12	2.08	0.05	0.10	0.05	0.03	41.95
KH-03	2.75	0.83	0.92	51.89	2.32	0.09	0.13	0.07	0.05	43.02
KH-04	1.45	0.58	0.72	54.05	1.89	0.06	0.08	0.04	0.02	41.12
KH-05	2.89	0.91	0.95	50.78	2.45	0.10	0.14	0.08	0.06	43.50

KH-06	1.67	0.63	0.81	53.68	2.01	0.07	0.09	0.05	0.03	41.98
KH-07	2.12	0.76	0.87	52.45	2.21	0.08	0.12	0.06	0.04	42.30
KH-08	1.89	0.69	0.78	53.89	1.94	0.06	0.11	0.05	0.03	41.85

Table 2: Trace Elements (ppm)

Sample ID	Sr	Ba	Zn	Mn	V	Cr	Ni	Cu	Pb	U	Th
KH-01	272	35	21	148	14	7	4	3	2	1.5	0.9
KH-02	265	38	18	153	12	6	3	4	2	1.3	0.8
KH-03	280	40	22	145	15	8	5	2	3	1.6	1.0
KH-04	258	32	17	159	11	5	3	4	2	1.2	0.7
KH-05	289	42	24	140	16	9	6	3	3	1.7	1.1
KH-06	270	34	20	150	13	6	4	2	2	1.4	0.8
KH-07	275	37	19	147	14	7	5	3	2	1.5	0.9
KH-08	262	33	18	155	12	6	3	4	2	1.3	0.8

Major Element Oxides

The dominant oxide in all samples is CaO, ranging from 50.78 wt% (KH-05) to 54.05 wt% (KH-04), indicating a high calcium carbonate content, which is desirable for cement production. The variations in CaO concentration across samples suggest slight compositional heterogeneity, which could be attributed to depositional conditions or post-depositional diagenetic processes. The MgO content ranges between 1.89 wt% (KH-04) and 2.45 wt% (KH-05), indicating that the limestone samples contain minor dolomitic components. Higher MgO levels can impact the clinkerization process in cement manufacturing, making it crucial to keep the MgO content within industry-accepted limits, which typically should not exceed 5 wt% for high-quality cement production.

The silica (SiO_2) content varies from 1.45 wt% (KH-04) to 2.89 wt% (KH-05). A higher SiO_2 concentration can influence the silica modulus, affecting the clinker quality and cement strength. The SiO_2/Al_2O_3 ratio also plays a crucial role in clinker formation; an optimal range enhances the production of alite (C_3S) and belite (C_2S) phases, which are essential for cement hydration reactions. Al_2O_3 content is generally low, ranging from 0.58 wt% (KH-04) to 0.91 wt% (KH-05), which suggests minimal clay or shale contamination. Fe_2O_3 levels are also relatively low, ranging between 0.72 wt% and 0.95 wt%, indicating limited ferruginous material presence.

The alkali oxides, Na_2O and K_2O, are present in trace amounts. Na_2O content ranges between 0.05 wt% and 0.10 wt%, whereas K_2O varies from 0.08 wt% to 0.14 wt%. These alkali elements are essential in controlling alkali-silica reactions (ASR) in concrete, which can lead to cracking and durability issues. The TiO_2 and P_2O_5 contents are both very low, typically below 0.08 wt%, indicating that the limestone has minimal phosphatic or heavy mineral impurities. The Loss on Ignition (LOI) values, ranging from 41.12 wt% (KH-04) to 43.50 wt% (KH-05), confirm a high carbonate content, consistent with the thermal decomposition of calcite ($CaCO_3 \rightarrow CaO + CO_2$). The variations in LOI values may be related to differences in the purity of carbonate minerals and the presence of minor clay fractions.

Trace Element Composition

Trace element concentrations in limestone provide insights into depositional conditions, diagenetic modifications, and potential industrial concerns. The trace element data obtained using ICP-MS analysis are presented in Table 2. Strontium (Sr) content ranges from 258 ppm (KH-04) to 289 ppm (KH-05), indicating a moderate Sr incorporation in calcite. Higher Sr levels are typically associated with marine carbonates, suggesting that the Khumnoh limestone may have been deposited in a shallow marine setting. Barium (Ba) is present in minor amounts, with values ranging from 32 ppm (KH-04) to 42 ppm (KH-05). Zinc (Zn) concentration varies from 17 ppm (KH-04) to 24 ppm (KH-05), and its presence may be linked to trace amounts of sulfide mineral inclusions or organic matter.

Manganese (Mn) concentrations range between 140 ppm and 159 ppm, with slightly elevated levels in certain samples, possibly due to diagenetic enrichment. Vanadium (V) concentrations are relatively low, ranging from 11 ppm to 16 ppm, and are generally associated with the presence of clay minerals or organic matter during sedimentation. Chromium (Cr) and Nickel (Ni) are found in small amounts, ranging from 5–9 ppm and 3–6 ppm, respectively. Their presence indicates minimal input from ultramafic or mafic detrital sources. Copper (Cu), Lead

(Pb), Uranium (U), and Thorium (Th) are present in trace amounts, with concentrations below 5 ppm, suggesting that the limestone is relatively pure and free from heavy metal contamination.

Comparison with Cement Industry Standards

For limestone to be used in cement manufacturing, it must meet specific chemical criteria set by industrial standards such as BIS 4032-2022 and ASTM C150. The CaO content in the analyzed samples falls within the ideal range for cement-grade limestone (≥ 50 wt%), confirming its suitability for clinker production. The MgO content, which should remain below 5 wt%, is within acceptable limits, ensuring that the limestone does not lead to excessive formation of periclase (MgO phase), which can cause expansion-related issues in cement.

The SiO_2 content, though relatively low, contributes to the formation of calcium silicate phases in clinker. A balanced SiO_2/Al_2O_3 ratio is essential to optimize cement properties, and the analyzed samples exhibit an acceptable range. The low alkali content ($Na_2O + K_2O$) ensures that the limestone does not pose a risk of alkali-silica reactivity (ASR), which can lead to long-term durability problems in concrete structures.

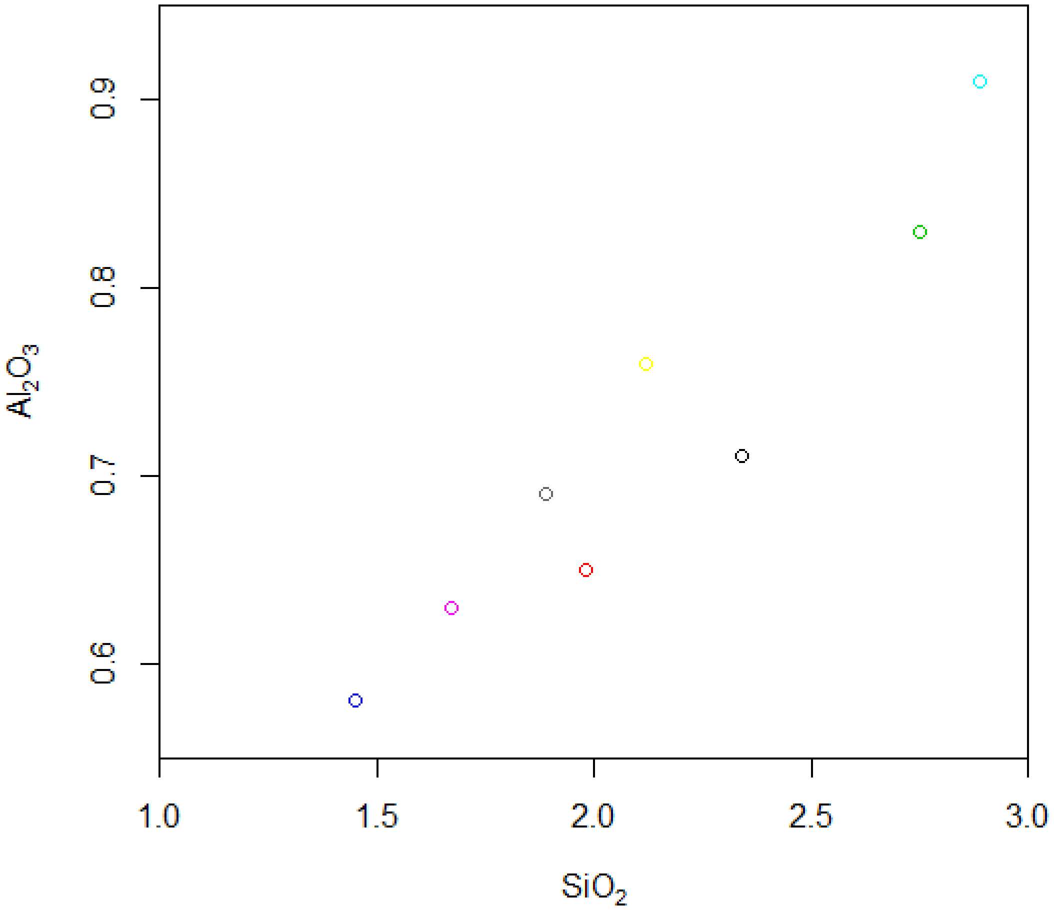


Figure 01: Variation of SiO_2 and Al_2O_3 concentrations in Khumnoh limestone samples. The low SiO_2 and Al_2O_3 contents indicate high chemical purity, making the limestone suitable for cement production. The compositional variations reflect depositional and diagenetic influences, with minimal siliceous or argillaceous impurities.

The SiO_2 and Al_2O_3 concentrations in the Khumnoh limestone samples are relatively low, indicating minimal siliceous and argillaceous impurities. This is a desirable trait for cement production, as excessive silica and alumina can affect clinker formation and require corrective materials such as clay and iron ore. The observed variations in SiO_2 (1.45–2.89 wt%) and Al_2O_3 (0.58–0.91 wt%) suggest minor compositional heterogeneity, potentially influenced by depositional conditions or localized impurities. The overall low levels confirm that the limestone is of high purity, suitable for clinker production with minimal beneficiation requirements. Trace elements, particularly Sr and Ba, are within permissible limits, ensuring that the limestone does not introduce undesirable impurities into the clinker. The presence of minor amounts of Fe_2O_3, Mn, and Zn is common in cement raw materials and does not adversely affect cement production.

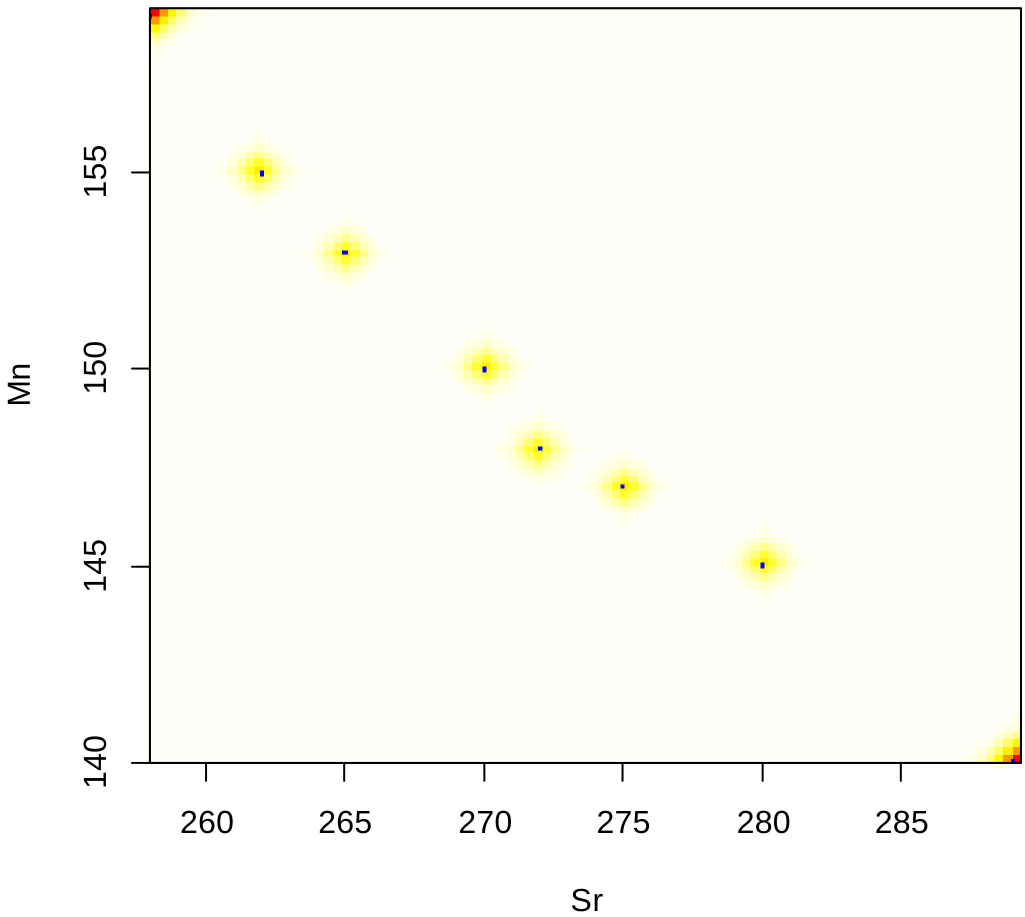


Figure 02: Sr and Mn concentrations in Khumnoh limestone samples. The moderate Sr levels suggest a shallow marine depositional setting, while the stable Mn values indicate limited diagenetic alteration. These factors contribute to the limestone's chemical stability and suitability for cement production.

Strontium (Sr): Sr concentrations range between 258 ppm and 289 ppm, with minor variations among the samples. Sr is commonly associated with marine carbonates, as it substitutes for Ca^{2+} in the calcite lattice. The moderate Sr content suggests a shallow marine depositional setting, with minimal diagenetic alteration leading to Sr depletion. Manganese (Mn): Mn concentrations vary from 140 ppm to 159 ppm, indicating diagenetic influences. Mn is typically incorporated into carbonate minerals during early diagenesis and can be an indicator of reducing conditions. The relatively stable Mn values across samples suggest limited post-depositional alteration, reinforcing the chemical purity of the limestone. The Sr-Mn relationship indicates that the limestone samples were deposited in a shallow marine environment, with minimal input from siliciclastic sources. The moderate Sr levels align with typical marine carbonate compositions, while the low Mn content suggests oxidizing conditions during deposition, reducing the likelihood of significant dolomitization or secondary mineral formation. These geochemical attributes support the suitability of the limestone for cement manufacturing, as they indicate stable mineralogy with minimal impurities.

Mineralogical Characteristics and Implications

The X-ray Diffraction (XRD) analysis confirms that calcite is the dominant mineral phase, with minor amounts of dolomite and trace impurities. The absence of significant quartz, feldspar, or clay minerals further supports the high purity of the limestone. This mineralogical composition is favorable for cement production, as excessive silicate or alumino-silicate minerals can interfere with clinkerization.

The mineralogical purity of the limestone influences the energy requirements in cement kilns. High-purity calcitic limestone requires lower energy for decomposition, reducing the overall fuel consumption and CO_2 emissions during clinker formation. Additionally, the low presence of clay minerals ensures minimal production of undesirable silicate phases, which can affect cement performance.

Geological Implications

The geochemical characteristics of the Khumnoh limestone suggest that it was deposited in a shallow marine environment with limited detrital input. The low Al_2O_3 and Fe_2O_3 contents, along with the high CaO and LOI values, indicate a clean carbonate system with minimal siliciclastic contamination. The moderate Sr content further supports a marine depositional setting, as Sr is typically enriched in marine carbonates. The variations in MgO and trace element concentrations across samples suggest slight diagenetic modifications, possibly related to minor dolomitization or fluid interactions. However, the overall chemical consistency across the samples indicates that the limestone maintains its original depositional characteristics.

Conclusion

The present study provides a comprehensive geochemical and mineralogical assessment of limestone samples from the Khumnoh area of Kashmir, evaluating their suitability for cement manufacturing. The results indicate that the limestone is of high purity, characterized by elevated CaO content (50.78–54.05 wt%), low MgO levels (1.89–2.45 wt%), and minimal silica and alumina impurities. The SiO_2 and Al_2O_3 concentrations remain below 3 wt% and 1 wt%, respectively, ensuring optimal raw material properties for clinker production. Furthermore, the low Fe_2O_3 content suggests that the limestone does not contain excessive ferruginous material, which could otherwise impact cement color and composition. The trace element analysis reveals that elements such as Sr, Ba, Mn, Zn, Cr, Ni, and Cu are present in permissible amounts, posing no risk to cement quality. The alkali content (Na_2O + K_2O) is also low, reducing the likelihood of alkali-silica reactivity (ASR) in concrete structures. Additionally, XRD analysis confirms that calcite is the dominant mineral phase, with only minor traces of dolomite and negligible silicate impurities, further validating its industrial potential.

A comparison with cement industry standards (BIS 4032-2022, ASTM C150) confirms that the chemical composition of the Khumnoh limestone meets the required specifications for high-quality clinker production. The Loss on Ignition (LOI) values (41.12–43.50 wt%) are consistent with a high carbonate content, reinforcing the limestone’s suitability for cement applications. Moreover, the low levels of phosphorus (P_2O_5) and titanium (TiO_2) indicate minimal interference with the cement manufacturing process. From a geological perspective, the chemical composition of the limestone suggests a shallow marine depositional environment with limited detrital input. The moderate Sr content (258–289 ppm) aligns with typical marine carbonate formations, while the variations in MgO and trace elements hint at minor diagenetic modifications.

Despite these variations, the overall compositional stability across the samples confirms the deposit's homogeneity, making it a reliable resource for industrial use. Khumnoh limestone exhibits excellent geochemical characteristics for cement production, with high calcium carbonate purity, low levels of undesirable oxides, and minimal trace element contamination. Given these attributes, the deposit presents a sustainable and viable raw material source for cement industries in the region. Future investigations may focus on petrographic studies, mechanical property testing, and kiln behavior analysis to further validate its performance in cement production. Additionally, economic feasibility assessments and resource estimation studies will be valuable for industrial-scale utilization and long-term resource planning.

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Conflicts of Interest

The authors declare no conflict of interest regarding the publication of this research.

Ethical Statement

This research was conducted in compliance with ethical scientific practices, ensuring accuracy, transparency, and integrity in data collection, analysis, and interpretation. No human or animal subjects were involved in this study.

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