

Optimum Utilization of Low-Grade Limestone by Modified Blending Method to Achieve Required Lime Saturation Factor in Cement Industry: A Sustainable Mining Approach in Sadhera and Salaiya Limestone Mines, Madhya Pradesh

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Abstract

The consumption of limestone in India has increased dramatically over time, under the impression of sprawling urban spheres and expanding industrial applications in cement industry. This elevated demand has posed India as the largest importer of limestone globally sourcing materials from various countries. The main objectives of the current study are to conduct geochemical analysis of the ore body and to develop a modified blending plan to optimize utilization of low-grade limestone. The study emphasizes on the importance of selective mining, proper blending, and sustainable extraction practices to maximize resource efficiency while minimizing environmental impact. In the current study borehole data of two limestone mines Sadhera and Salaiya were employed for proper utilization of low-grade limestones. The distribution of CaO content exhibits remarkable variation along the deposit with minimum value at 34.14% upto 50% as highest value at Sadhera mine while these values range between at 40.26% to 43.84% Salaiya mine. As per the IBM, threshold values for CaO and MgO are 34% and 5% respectively which can be attained by strategic blending of low- and high-grade limestones. For Sadhera and Salaiya mines, the statistical analysis depicts CaO exhibiting negative skewness in normal distribution. Also, the correlation analysis exhibits strong correlation of CaO with SiO₂ and Al₂O₃. The modified beneficiation method represents a substantial 49% and 12% increase for Salaiya and Sadhera mines indicating towards improvised quality criteria, extended mining limits, or inclusion of low-grade zones earlier ignored in the mining operations. The modified LSF of 149% and 112% indicates a comprehensive reevaluation of the resource potential, with possible incorporation of improved updated economic factors. The findings of the study revealed an overall 25% increase in resource estimation, indicating the presence of deeper and previously unaccounted reserves. Such analysis plays a vital role in guiding efficient extraction planning and optimizing resource utilization. The inclusion of marginal limestone deposits along with the revised evaluation techniques and blending methodologies offers an overall enhanced mineral recovery across the mining sites. Such enhancement of mineral utility ensures not only longevity of the mine life but also results in significant reduction in overburden and inter-burden waste leading to sustainable mining practices.

Keywords: Limestone, Lime Saturation factor, Blending, Sustainable Mining, Resource Estimation.

1. INTRODUCTION

Limestone, primarily composed of calcium carbonate, is one of the most abundant sedimentary rocks on Earth and serves as a fundamental material in various industrial applications (Oates, 1998; Scrivener et al., 2018). The industrial significance of limestone extends beyond cement production and includes critical applications in steel manufacturing, construction, food and beverage processing, and pharmaceutical industries. The mineral is also crucial for other aspects like environmental rehabilitation, due its ability to neutralize acidic pollutants which renders it essential in wastewater treatment and soil stabilization initiatives. Limestone serves as an essential flux in metallurgical processes, facilitating in impurity removal and improving metal purification efficiency (Azapagic, A. 2004). Globally, limestone deposits are distributed across multiple geological formations, with significant reserves found in North America, Europe, Asia, and Australia (Boynton, 1980; Tucker & Wright, 1990). These deposits exhibit considerable variations in their chemical composition, physical properties, and geological age, influencing their suitability for different industrial applications (Deer et al., 1992). India possesses vast reserves and resources of limestone, estimated to be around 227.58 billion tonnes, positioning it as one of the prominent nations in terms of limestone availability (Indian Mineral Year Book, 2022). These deposits are extensively distributed across various states and are essential in supporting India's cement, steel, construction, food,

pharmaceutical, and packaging sectors. The distribution of limestone resources in India exhibits significant geographic variations. Karnataka alone holds the largest reserves with approximately 27% of the total reserve, while Andhra Pradesh and Rajasthan are second in rank with about 12% each (Anurag Bagaria, 2019). Gujarat, Meghalaya, and Telangana contribute 10%, 9%, and 8% respectively, while Madhya Pradesh and Chhattisgarh account for about 5% of the reserves each. Among these states, Madhya Pradesh emerges as a significant contributor, hosting nearly 9.65 billion tonnes of limestone reserves (Indian Mineral Year Book, 2022, Geological Survey of India, 2018; Indian Bureau of Mines, 2020).

The consumption of limestone in India has increased dramatically over the time, which has posed India as the largest importer of limestone globally, sourcing materials from countries including Bangladesh, the United Kingdom, and Bhutan (Anurag Bagaria, 2019). The rising import trend over the past decade highlights the widening gap between domestic demand and supply, underlining the urgent need for improvised domestic mining initiatives and refined resource management strategies. Limestone classification for cement manufacturing is primarily determined by its chemical composition, particularly calcium oxide (CaO), silica (SiO₂), and magnesium oxide (MgO) content (Taylor, 1997; Hewlett, 2003). Limestone can be categorized into various grades based on its calcium oxide (CaO) and silica (SiO₂) percentage, with cement-grade limestone particularly requiring specific chemical parameters to ensure optimal clinker formation (Duda, 1985; Lea, 1970). The Bureau of Indian Standards has specified the characteristics of limestone deposits in several Indian states which includes CaO - 35% (minimum), MgO - 4% (maximum), SiO₂ - 18% (maximum) & Alkalies - 0.5% (maximum) (Singh et. al., 2013). The grading system classifies the limestone in three categories: high-grade limestone (>48% CaO), medium-grade limestone (40-48% CaO), and low-grade limestone (<40% CaO) (Jawed et al., 1983; Singh, 2006).

Within Madhya Pradesh, Maihar district emerges as a notable region due to its rich limestone deposits. known for its superior-grade limestone. The exceptional high quality and abundance of limestone deposits in Maihar have drawn significant investment from leading cement manufacturing companies, resulting in the establishment of multiple production facilities transforming the area into a prominent cement production hub within Madhya Pradesh's industrial landscape (Cement Manufacturers Association, 2019). This huge industrial expanse reflects the broader context, wherein the country's substantial limestone endowments have positioned the country as the second-largest cement producer in the global market, underscoring the strategic importance of the region in supporting India's industrial growth and infrastructure development objectives. The increasing demand of Limestone in future will change the prospective of resource utilization and its demand. To keep the balance of demand and supply in entire life of mine it is necessary to utilize maximum resources available in the mining lease. The main objectives of the study are to conduct geochemical analysis of the ore body and to develop a modified blending plan to optimize utilization of low-grade limestone.

2. STUDY AREA

Study area located in the Maihar district of Madhya Pradesh, India, is geologically situated within the Vindhyan Basin, one of the significant Proterozoic sedimentary basins in India. The region is predominantly characterized by sedimentary rock formations, including sandstone, shale, and limestone, which are part of the Vindhyan Supergroup. The Vindhyan Basin is subdivided in four groups - Semri group, Kaimur group, Rewa group and Bhandar group. The Semri Group constitutes the basal unit of the Vindhyan Supergroup and represents the earliest sedimentation phase in the basin (Srivastava et.al., 2003). The Semri group comprises of Basal Sandstone, Kheinjua Shale, Kajrahat Limestone and Rohtas Limestone. The Semri Group is mostly composed of thick unmetamorphosed and undeformed sedimentary sequences of Late Palaeoproterozoic age (Bose et al., 2001; Ray, 2006). The Kaimur group comprising of Sasaram sandstone, Kaimur conglomerate and Dhandraul sandstone is an assemblage of sandstone, shale flagstone and porcellanites. The rocks of Rewa group consist of thick diamondiferous conglomerates, sandstones, shale and panna shale which are well exposed in Panna and Satna districts (Soni et. al., 1987). The Rewa group comprises of Upper Rewa Sandstone, Jhiri Shale, Lower Rewa Sandstone and Panna Shale. The Bhandar Group constitutes the youngest group of the Vindhyan basin. The Bhandar Group comprising of the Ganurgarh Shale, the Bhandar Limestone, the Sirbu Shale and the Maihar Sandstone is made up of sandstone, shale and stromatolitic limestone.

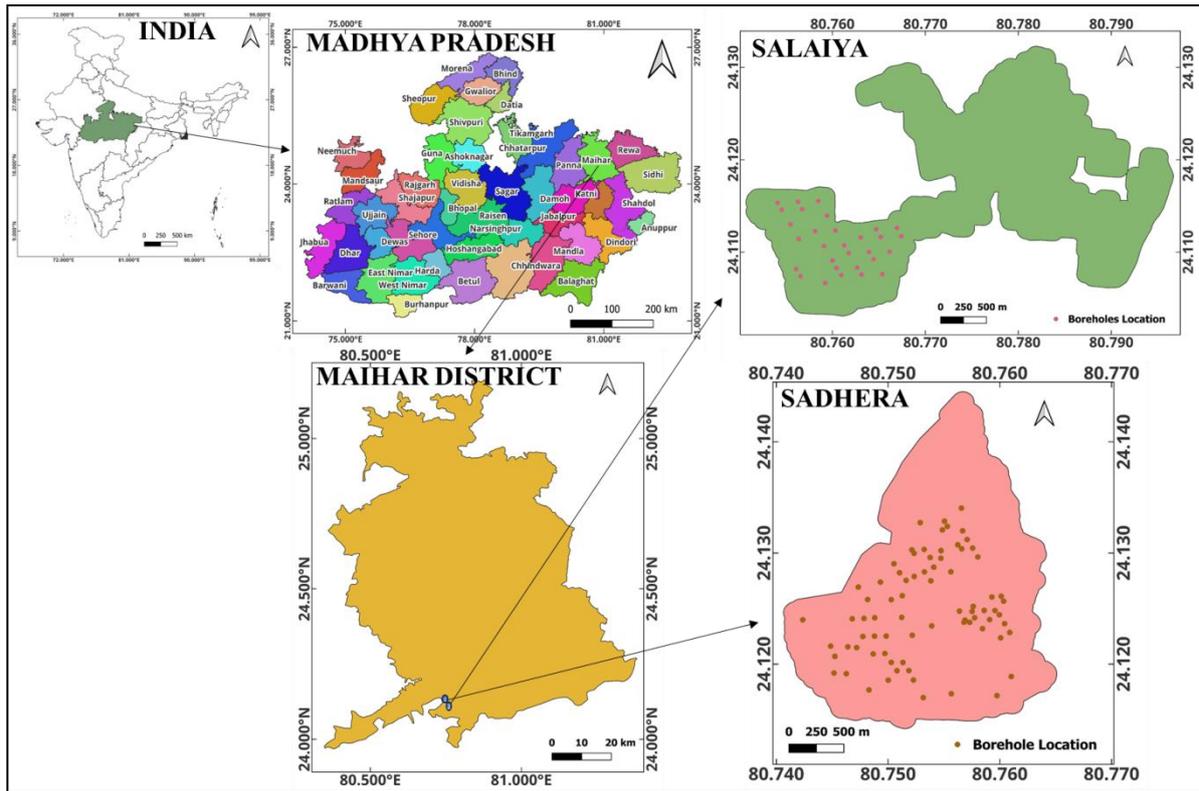


Figure 1: Location of Research Area with bore hole locations plotted (Source: Mapsfindia.com and Approved Mining Plan)

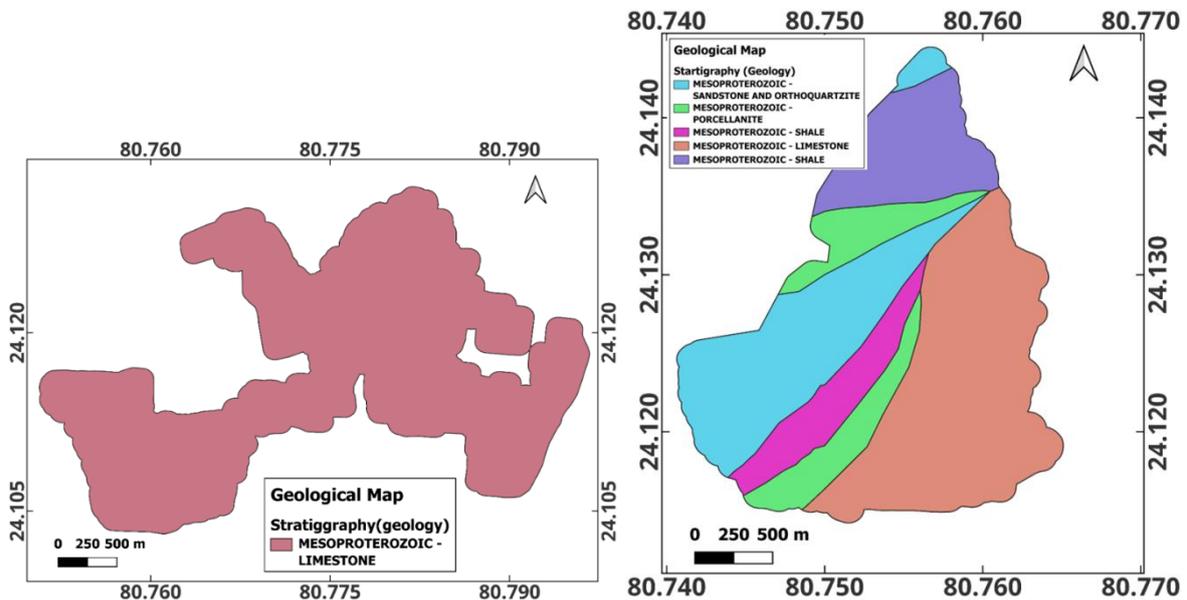


Figure 2: Geological Map of Salaiya and Sadhera

The study area typically endows the lithology of Semri Group of the Lower Vindhyan Group (Figure 1 and 2). The geological setting of Maihar also includes various structural features such as folds and faults, which have influenced the distribution and orientation of these sedimentary units (Sarkar et. al., 2020). Overall, the geological setup of Maihar is significant due to its rich sedimentary formations, particularly the limestone deposits, which have implications for both academic research and industrial applications. The limestone deposit of the study area is mainly of stromatolitic type with a nodular look and belongs to the Rohtas Limestone of Semri series group (Sharma and Shukla, 2009). The study area comes under a part of the Semri Series of the Lower Vindhyan System of the Indian Stratigraphy. G.S.I. had carried out the geological mapping of the area

and given the lithological sequences. Rohtas Limestone is typically associated with the Semri Group, one of the oldest formations in the Vindhyan basin. The Vindhyan rocks are primarily sedimentary, with extensive deposits of limestone and shale. The Rohtash formation found in the study area including Limestone and Shale is important for manufacturing of cement. During the field study it was also observed that the area is structurally disturbed and gives a complicated picture for a limestone deposit of Lower Vindhyan age. The limestone beds are folded as seen from their attitudes measured on outcrops. Some field photographs showing the structural disturbance in Limestone Deposit of study area are given in figure 3.



Figure 3: Field Photographs showing structural disturbance in Limestone Deposits

3. DATA AND METHODOLOGY

3.1. Collection of Primary data: Detailed field work was carried out in the Rohtas Limestone formation of the Maihar District (M.P.). Further different litho-units were identified (High Grade Limestone i.e. cut-off grade and low-grade limestone i.e. above IBM Threshold Value). The data for current study is provided by M/s RCCPL Pvt. Ltd. The geological cross section was studied for the deposit evaluation in order to understand the stratigraphy, lithology and structural setting of the area. Total 112 bore holes were analyzed systematically to conduct deposit evaluation on the basis of cross-sectional method and maximum utilization of low-grade material through proper blending to meet the required quality. The methodology adopted compares the current raw mix composition for cement grade limestone based on NCCBM norms and IBM threshold with mine planning (Ministry of Mines, 2015). The research methodology employs a systematic approach, integrating both qualitative and quantitative methods to collect and analyze data related to limestone deposits in Maihar District. The research utilizes statistical and analytical tools to ensure accuracy and reliability of results through a structured framework designed to achieve the research objectives. The reserve estimation was conducted and XRF analysis of the bore hole core samples was done.

3.2. Reserves Estimation: This involves determining the volume, grade and tonnage of the mineral present. The basic principle of ore reserve estimation is based on employing the formula of tonnage calculation to estimate the economic viability of the ore deposit (Evans, 2013). The unit of estimation is tonne (t) and formula is –

Tonnage (t) = Volume (V) x Specific Gravity (Bulk density)

The current research employed Data Mine software along with cross-section method.

3.3. Lime Saturation Factor (LSF): The calculation of the Lime Saturation Factor (LSF) is essential in designing the raw mix for Cement Manufacturing, as it ensures the appropriate proportion of lime relative to other major oxides such as Silica (SiO₂), Alumina (Al₂O₃), and Iron Oxide (Fe₂O₃). Mathematically, LSF is expressed by the formula –

$$LSF = \frac{CaO \times 100}{2.8 \times SiO_2 + 1.18 \times Al_2O_3 + 0.65 \times Fe_2O_3}$$

4. RESULTS

In the current study, the focus is on limestone used for cement manufacturing, which demands large volumes of high-quality raw material. The limestone in the area exhibits variation in thickness and quality however good-quality limestone is found even below thick inter-burden layers. Extracting this deep situated second-band limestone is vital for cement units. Total 82 Bore Holes of Sadhera Limestone Mines (Latitude 240 06' 54.34" to 240 08' 37.7" and Longitude 800 44' 29.85" to 800 45' 50.05") and 30 Bore Holes of Salaiya Limestone Mines (Latitude 240 06' 14.31" to 240 07' 52.98" and Longitude 800 45' 06.10" to 800 47' 44.52") of M/s RCCPL Private Limited have been analyzed during research work. The deeper bands deposited below the inter-burden representing low grade limestone can be used for strategic blending to enhance the cement production. For effective economic extraction of the limestone deposits stripping ratio, a critical surface mining parameter representing the overburden-to-ore ratio should be employed in mine planning. The lower stripping ratios indicate efficient operations with reduced waste, while higher ratios increase costs and environmental impact.

Table 1: Quantity of second band limestone in the deposit in the study area

Sl. No.	BH No.	Lst. Depth	Lst. Volume M3	Lst. Tonnage MT	Sl. No.	BH No.	Lst. Depth	Lst. Volume M3	Lst. Tonnage MT	
1	1	19.15	7660	19150	19	31	22.25	8900	22250	
2	2	3.50	1400	3500	20	32	19.70	7880	19700	
3	4	3.50	1400	3500	21	33	3.00	1200	3000	
4	5	11.00	4400	11000	22	34	3.20	1280	3200	
5	6	1.75	700	1750	23	37	19.60	7840	19600	
6	7	2.45	980	2450	24	38	13.90	5560	13900	
7	8	3.75	1500	3750	25	39	1.50	600	1500	
8	9	13.50	5400	13500	26	41	4.60	1840	4600	
9	10	9.50	3800	9500	27	48	1.50	600	1500	
10	11	13.17	5268	13170	28	53	29.50	11800	29500	
11	12	7.00	2800	7000	29	55	3.00	1200	3000	
12	21	5.00	2000	5000	30	56	7.40	2960	7400	
13	24	23.55	9420	23550	31	64	1.25	500	1250	
14	25	4.50	1800	4500	32	68	3.55	1420	3550	
15	27	39.50	15800	39500	33	73	5.40	2160	5400	
16	28	7.00	2800	7000	34	76	10.00	4000	10000	
17	29	20.50	8200	20500	35	79	11.00	4400	11000	
18	30	28.60	11440	28600	36	80	5.30	2120	5300	
Total				216920	Total				165650	

4.1. Borehole Analyses, Scatter Plots and Histograms of Sadhera

Considerably large dataset consisting of 82 boreholes drilled at depths between 4.80 meters to 107.30 meters exhibits significant variations in chemical and lithological composition. Numerous boreholes demonstrated extreme depth which indicated towards substantial mineralization at significant depths. The distribution of CaO content exhibits remarkable variation along the deposit with minimum value at 34.14% upto 50% as highest value. Examples of such high CaO content boreholes are borehole 75 with 50% CaO, borehole 62 with 49.59% CaO and borehole 61 with 49.11% CaO content. Conversely few other boreholes such as borehole 49 showing marginal CaO content around 40.01% to 36.53% suggest quality degradation with increase in depth.

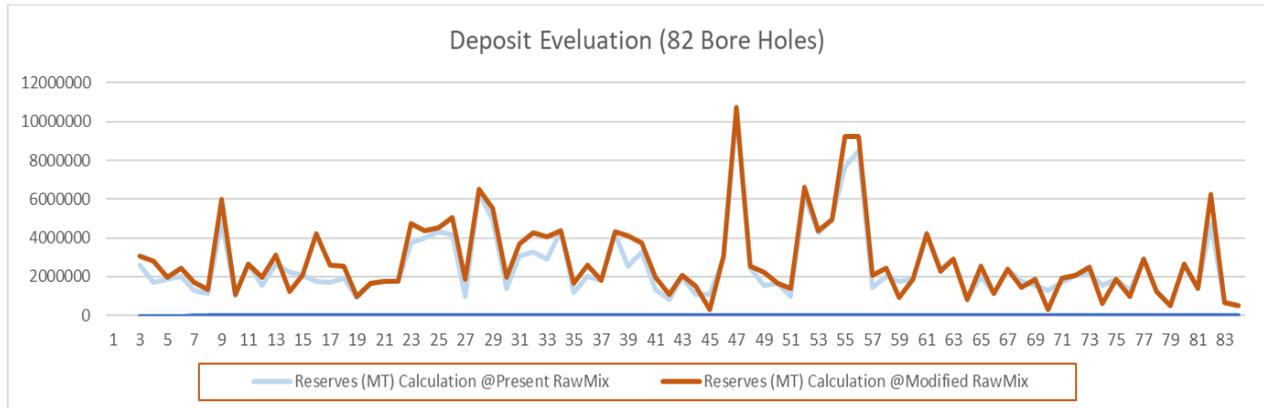


Figure 4: Linear/Graphical representation of deposit evaluation of Sadhera Limestone Mines

The magnesium oxide content of the boreholes exhibits acceptable levels with increasing levels under the new adopted methodology from 3.53% to 3.87% still remaining below the maximum threshold limit of 5%. However, at some instances few boreholes exhibit MgO content exceeding the threshold limit. Few examples of such boreholes are borehole 35 with 8.18% to 8.81% MgO content and borehole 13 with 6.50% MgO content. Such zones possessing high MgO contents offer potential processing challenges and necessitate selective mining and beneficiation strategies to ensure required product quality. The comparison between the currently employed methodology and proposed improvised methodology indicates towards substantial disparities between the resource estimation approaches and their repercussions for the mining operations. The current resource estimation considers high quality limestone resource with weighted average at 44.58% CaO content and 3.53% MgO content while the suggested improvised methodology indicates 42.44% CaO content and 3.87% MgO content leading to incorporation of wider raw material resources by considering the marginal limestone zones for mineral exploration.

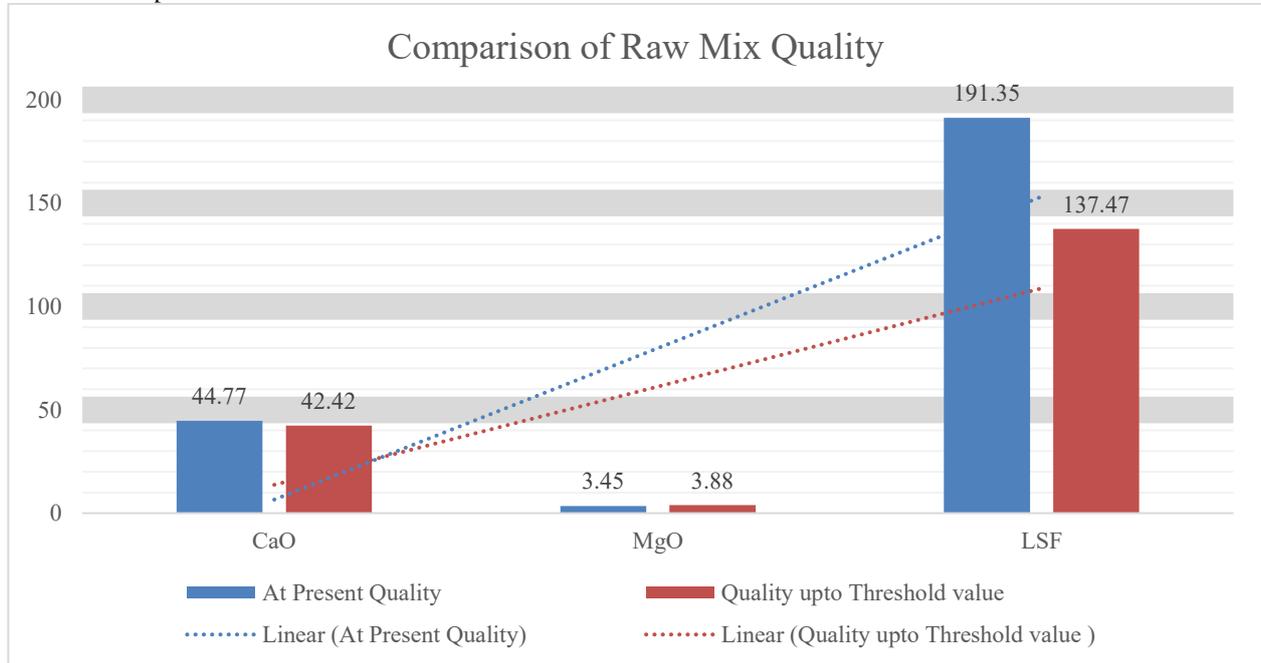


Figure 5: Graphical representations showing the comparison of Raw Mix Quality in Sadhera Deposit

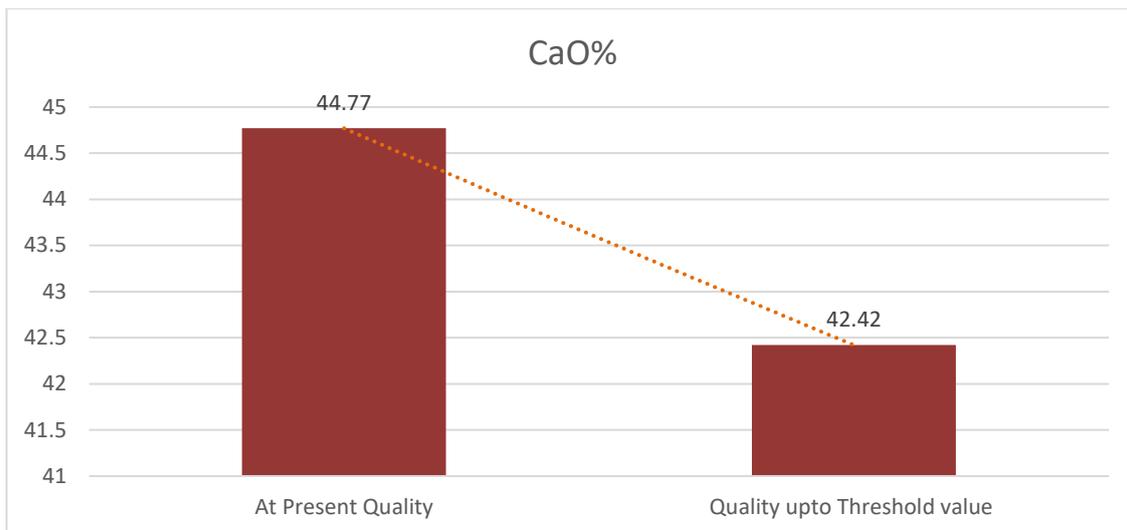


Figure 6: Graphical representation showing comparison in the CaO% in Sadhera Deposit

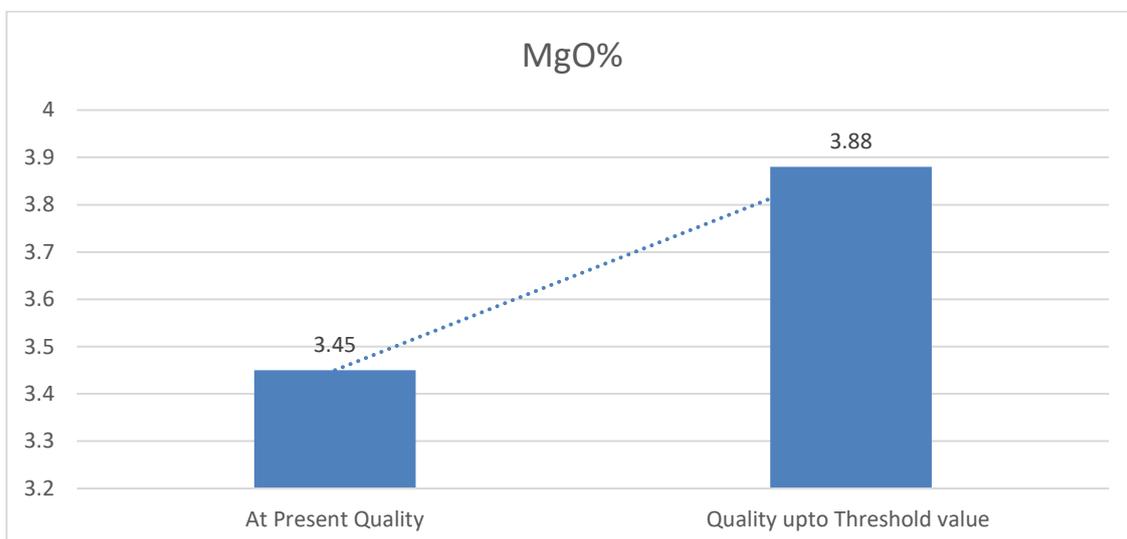


Figure 7: Graphical representation showing comparison in the MgO% in Sadhera Deposit

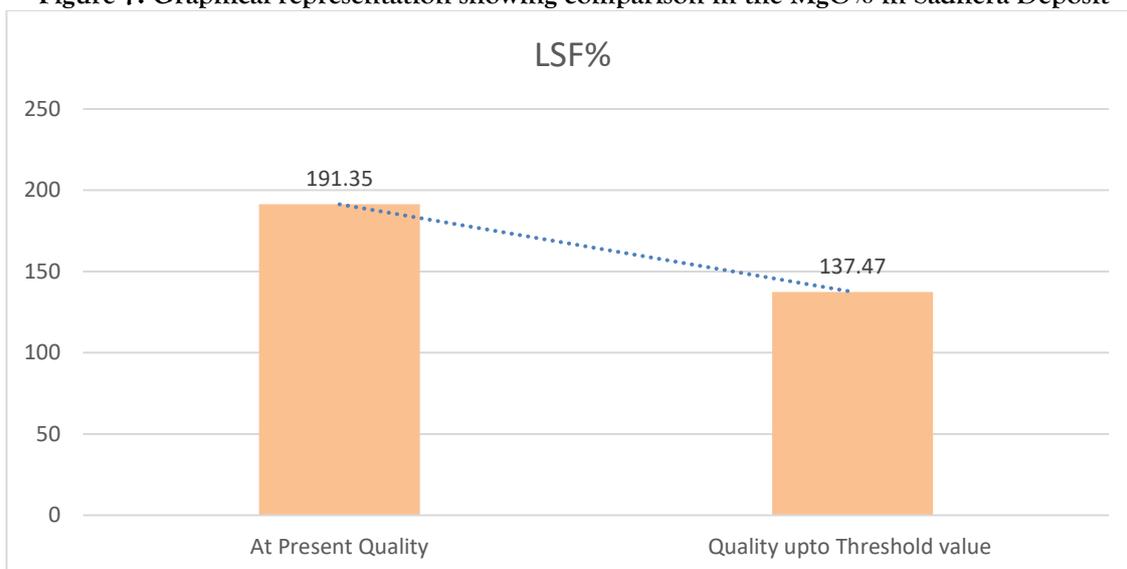


Figure 8: Graphical representation showing comparison in the LSF% in Sadhera Deposit

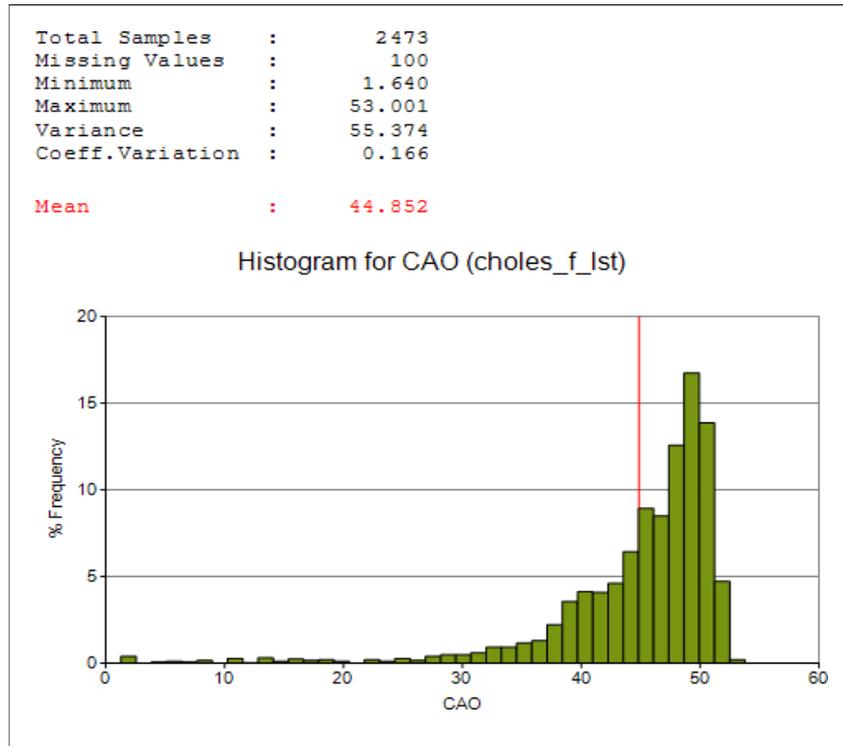


Figure 9 (a): Frequency distribution of CaO values within ore (limestone body)

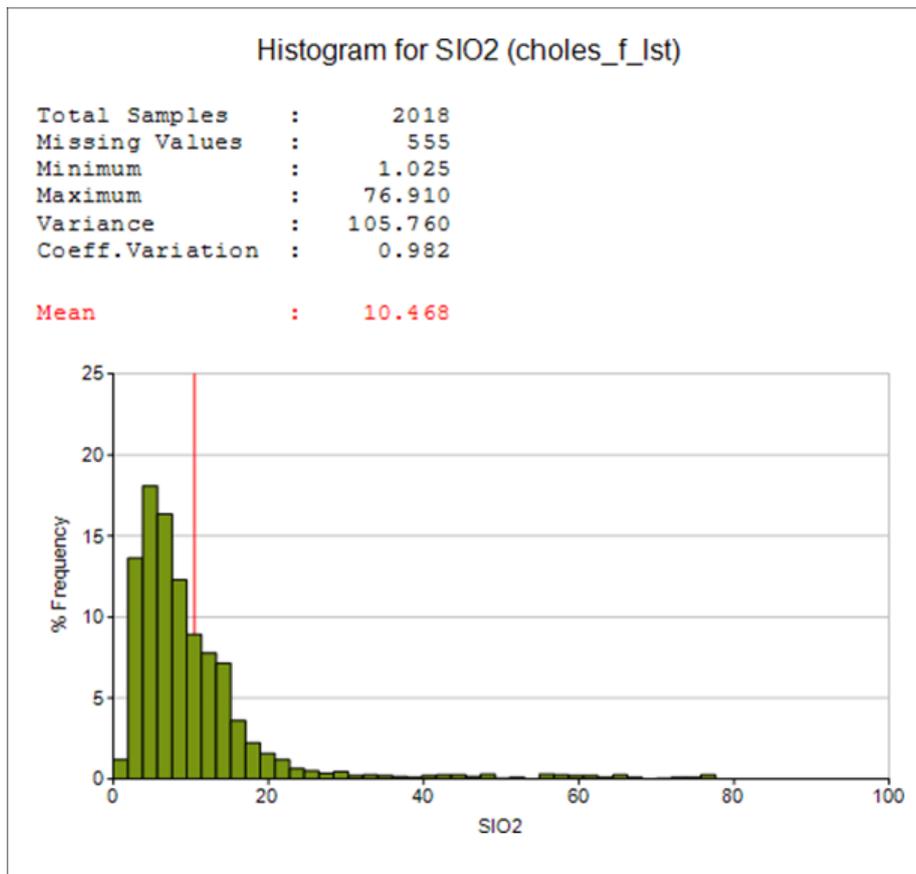


Figure 9 (b): Frequency Distribution of SiO₂ values within ore (limestone body)

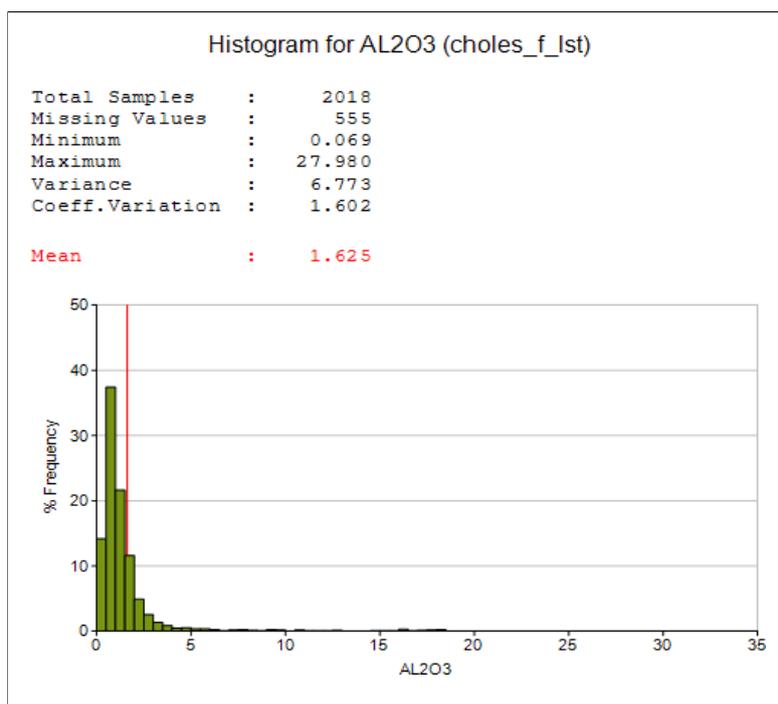


Figure 9 (c): Frequency Distribution of Al₂O₃ values within ore (limestone body)

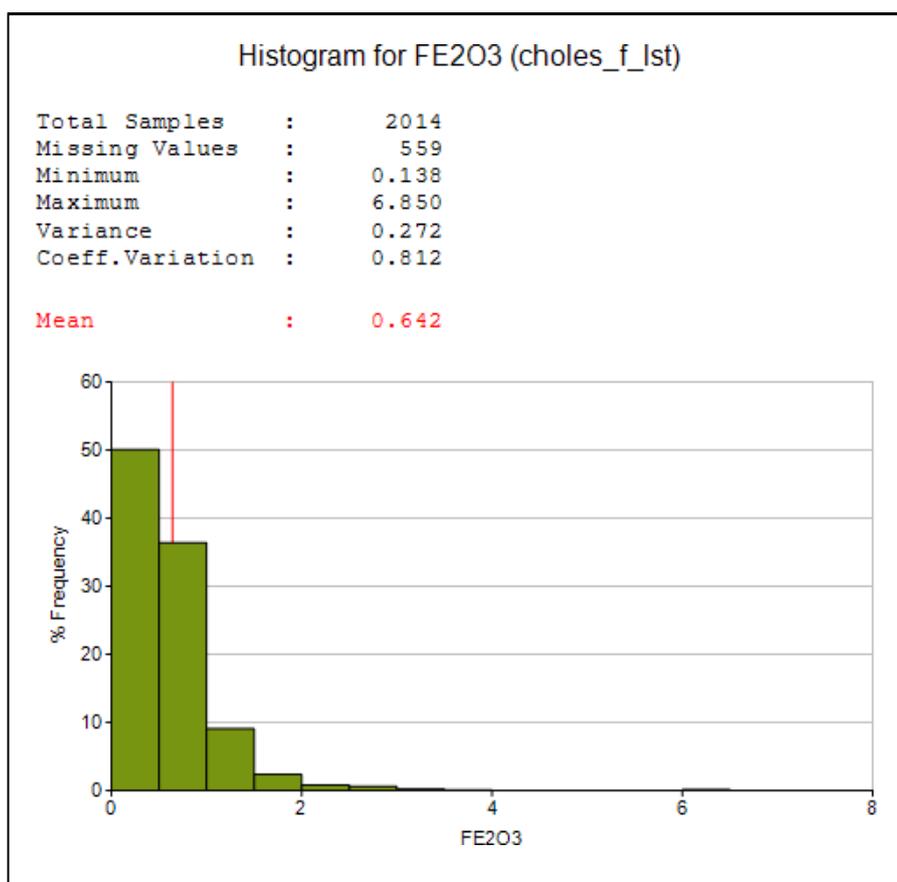


Figure 9 (d): Frequency Distribution of Fe₂O₃ values within ore (limestone body)

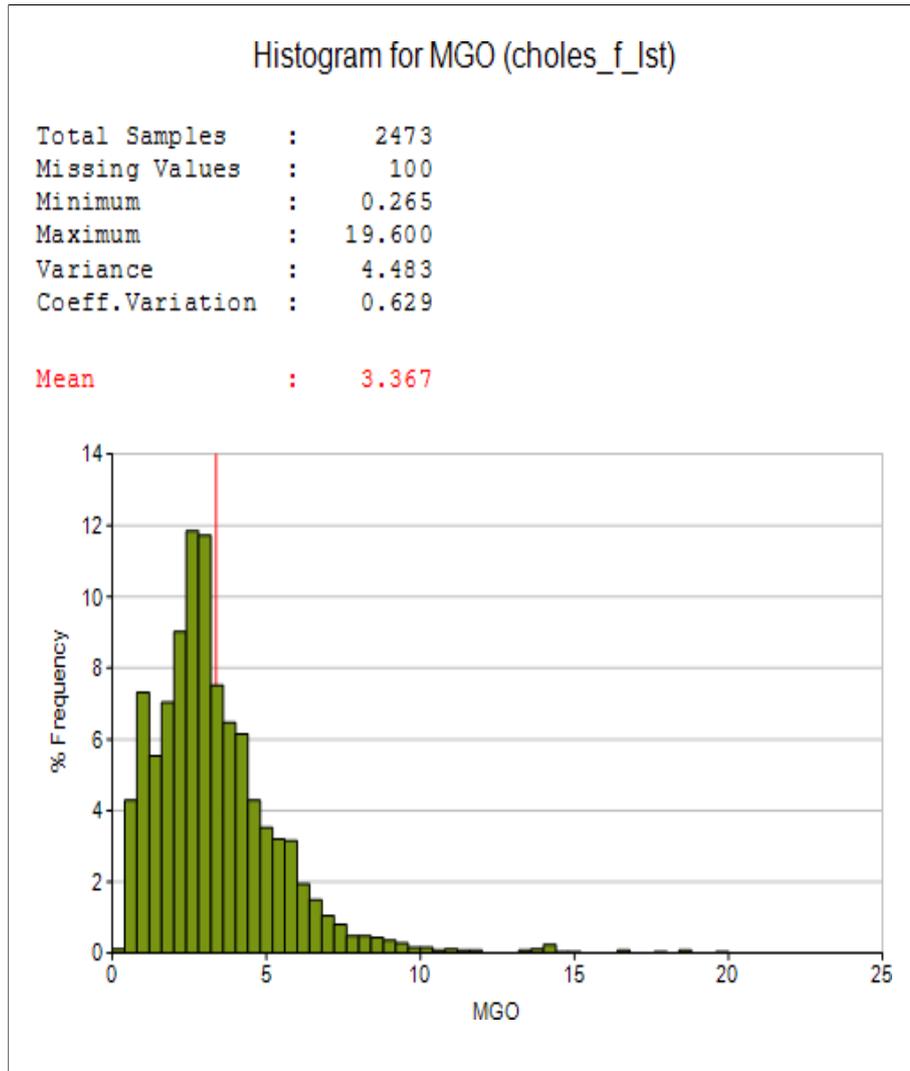


Figure 9 (e): Frequency Distribution of MgO values within ore (limestone body)

Table 2: Statistics on samples within interpreted orebody (CaO>38%)

FIELD	CaO	SiO ₂	MgO	Fe ₂ O ₃	Al ₂ O ₃	SM	AM
NSAMPLES	2473	2018	2473	2014	2018	2018	2014
MINIMUM	1.64	1.02	0.27	0.14	0.07	1.24	0.22
MAXIMUM	53.00	76.91	19.60	6.85	27.98	15.94	21.79
RANGE	51.36	75.89	19.33	6.71	27.91	14.70	21.57
MEAN	44.85	10.47	3.37	0.64	1.62	5.22	2.21
VARIANCE	55.37	105.76	4.48	0.27	6.77	2.59	3.38
STAND DEV	7.44	10.28	2.12	0.52	2.60	1.61	1.84
STAND ERR	0.15	0.23	0.04	0.01	0.06	0.04	0.04
SKEWNESS	-2.72	3.52	2.11	5.00	5.20	1.32	5.91
KURTOSIS	9.81	15.17	8.75	42.78	31.43	4.12	40.76

Statistical analysis has been carried out considering only the samples within the mineralised body above a cutoff grade of 38% CaO. The statistical parameters have been calculated for all the radicals. It can be seen from the distribution of CaO, SiO₂, Fe₂O₃, Al₂O₃, MgO that these show near normal distributions with CaO showing a negative skewness whereas others show a positive skewness (Figure 9a, 9b, 9c, 9d, 9e and Table 2).

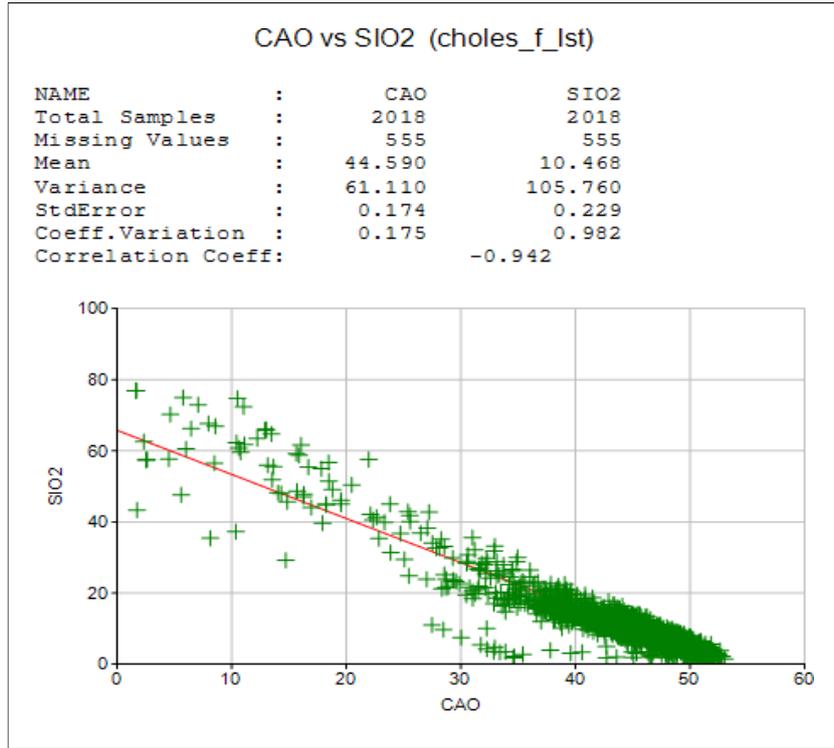


Figure 10 (a): Scatter plot showing relationship between CaO and SiO₂

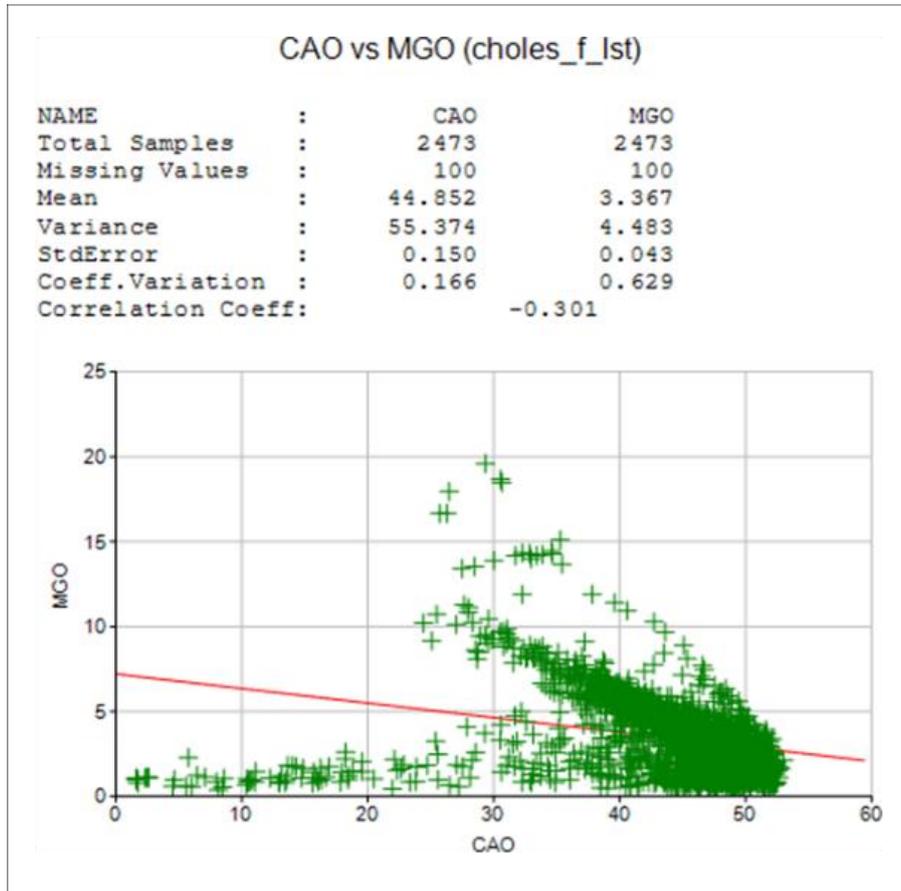


Figure 10 (b): Scatter plot showing relationship between CaO and MgO

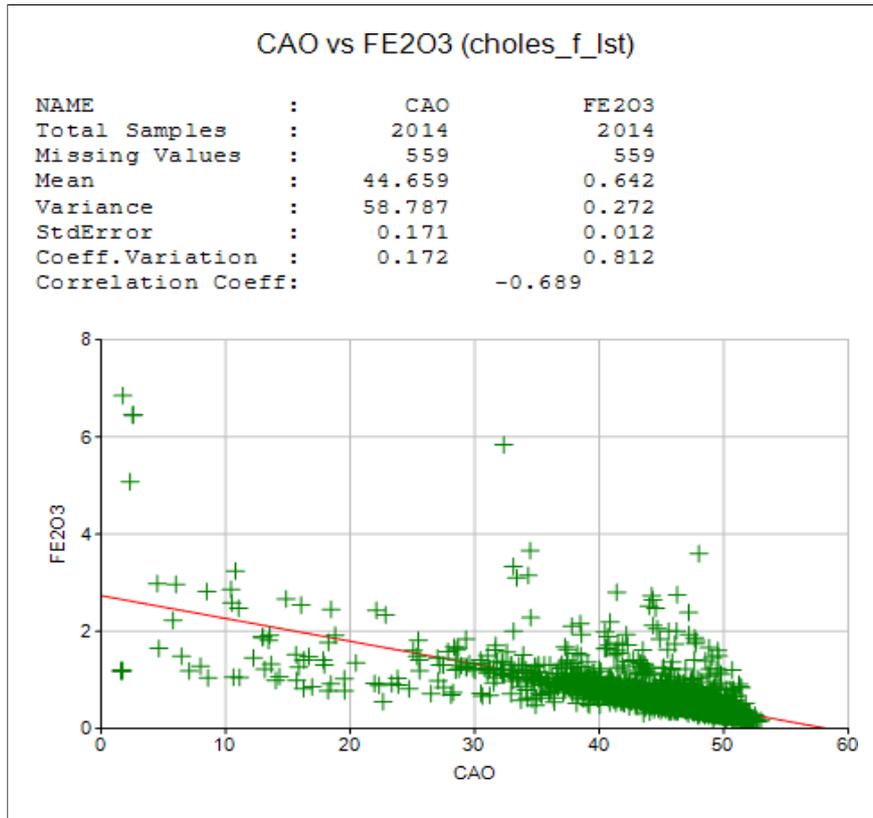


Figure 10 (c): Scatter plot showing relationship between CaO and Fe₂O₃

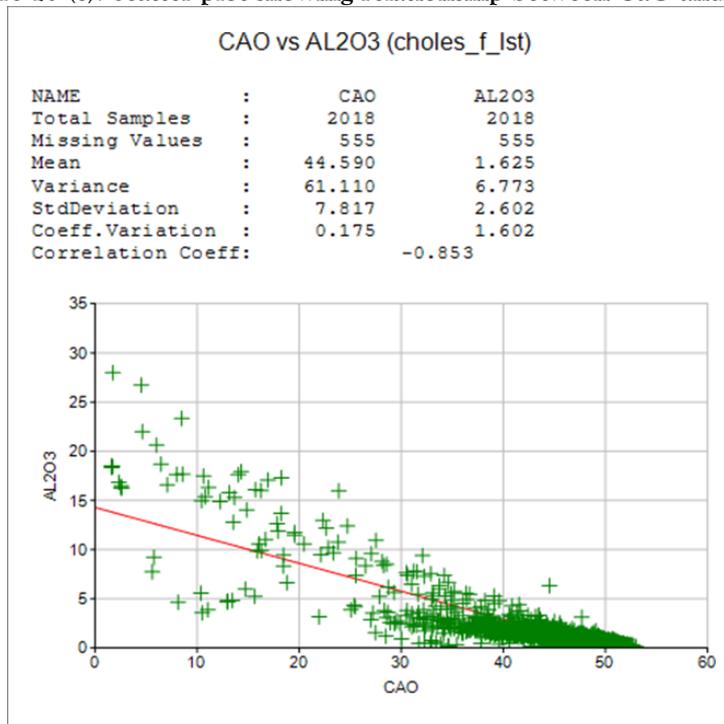


Figure 10 (d): Scatter plot showing relationship between CaO and Al₂O₃

From the correlation study, it can be inferred that although there exists strong correlation between CaO and SiO₂ (-0.94) & CaO and Al₂O₃ (-0.85), the correlation between CaO vs. MgO (-0.30) & MgO vs Fe₂O₃(0.01); Al₂O₃ vs Fe₂O₃ (0.59) are not very significant. With the Correlation study of different radicals, it is inferred that it is statistically insignificant except CaO and SiO₂ (Figure 10a, 10b, 10c and 10d).

4.2. Borehole Analyses, Scatter Plots and Histograms of Salaiya

The borehole data exhibits distinct compositional patterns varying significantly with depth, indicating clear geological demarcation within the deposit. Shallow intervals ranging from 0.5m to 4.6m in thickness within the 0-5m depth range typically demonstrate the highest calcium oxide concentrations, with CaO percentages ranging from 40.26% to 43.84% and maintaining an average of approximately 41.5%. Medium depth intervals lying at 5-10m depth range, show greater variability in both thickness and chemical composition. At these depths thickness varies from 1.35m to 8.0m, with CaO composition ranging from 34.63% to 42.80%. Intervals deeper than 10m depth has limited data availability however the available data shows CaO% ranging between 35.75% to 39.98%.

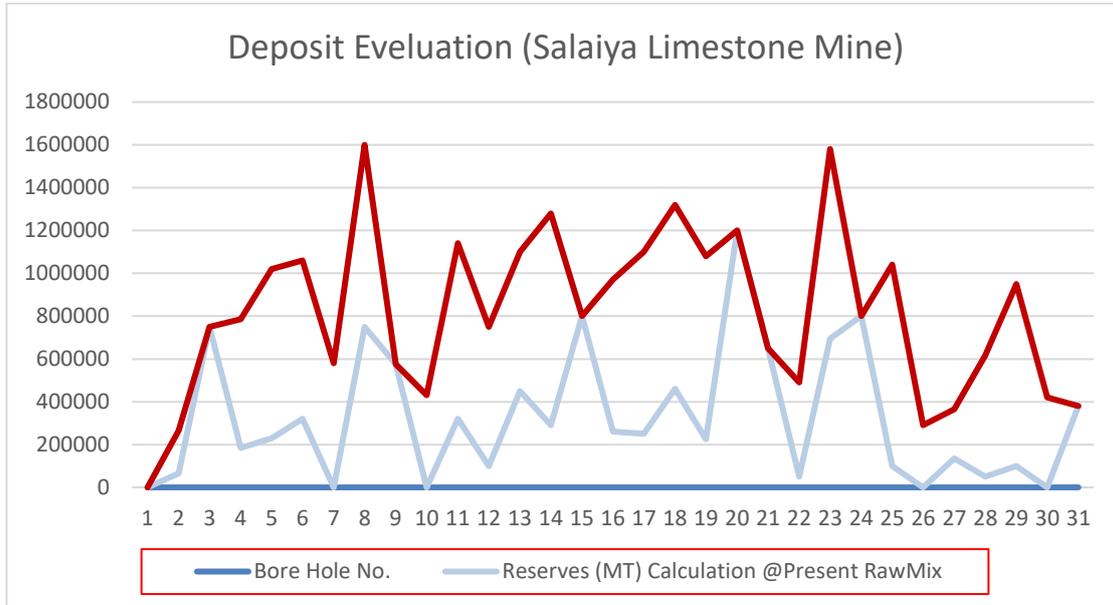


Figure 11: Linear/Graphical representation of deposit evaluation of Salaiya Limestone Mines

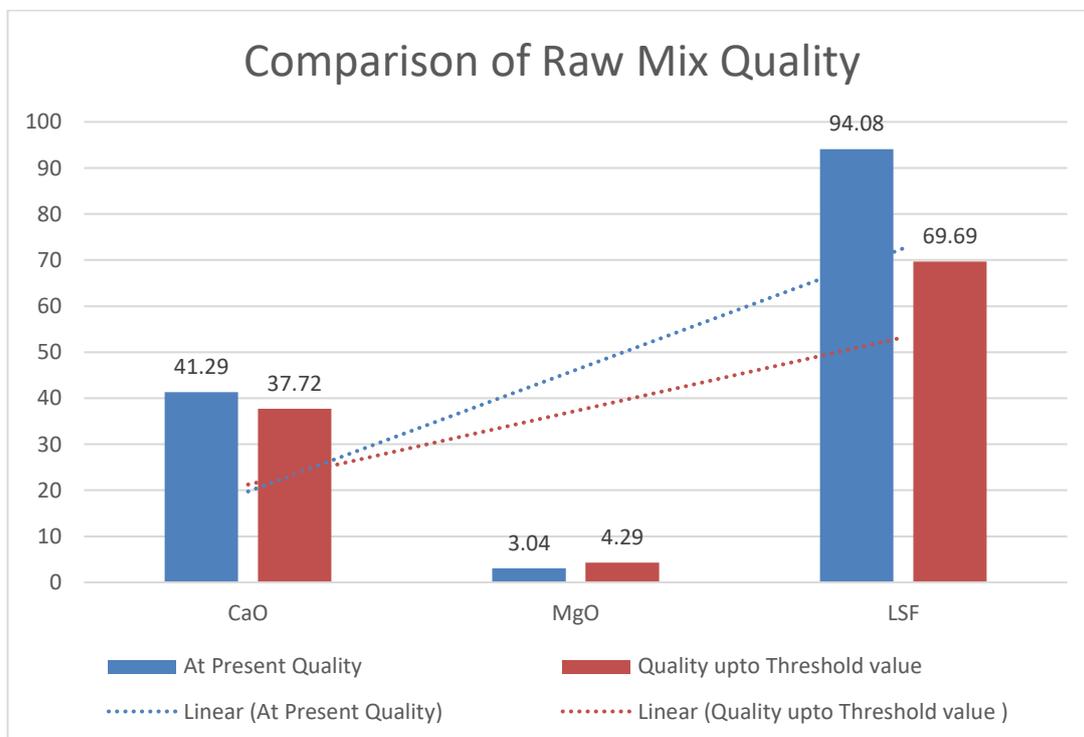


Figure 12: Graphical representation showing comparison of Raw Mix Quality in Salaiya Deposit

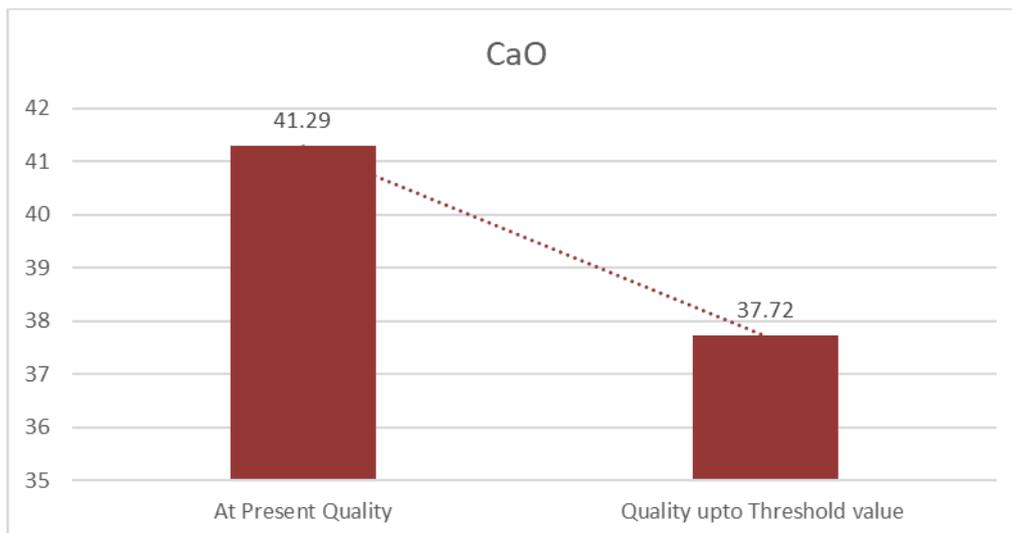


Figure 13: Graphical representation showing comparison in the CaO% in Salaiya Deposit

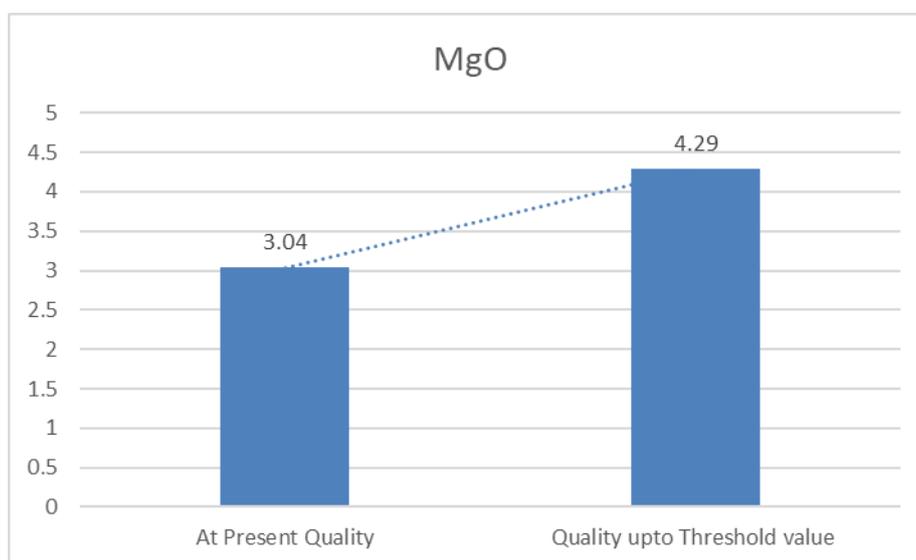


Figure 14: Graphical representation showing comparison in the MgO% in Salaiya Deposit

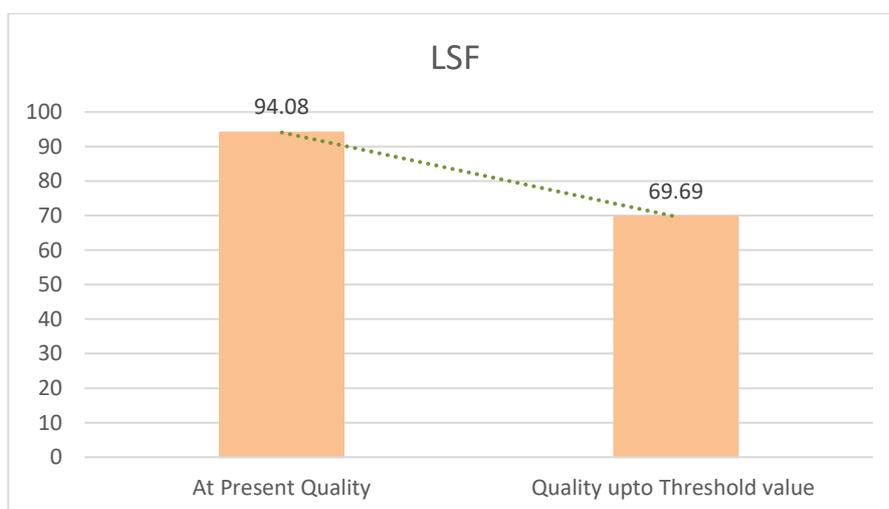


Figure 15: Graphical representation showing comparison in the LSF% in Salaiya Deposit

Cumulative Discussion

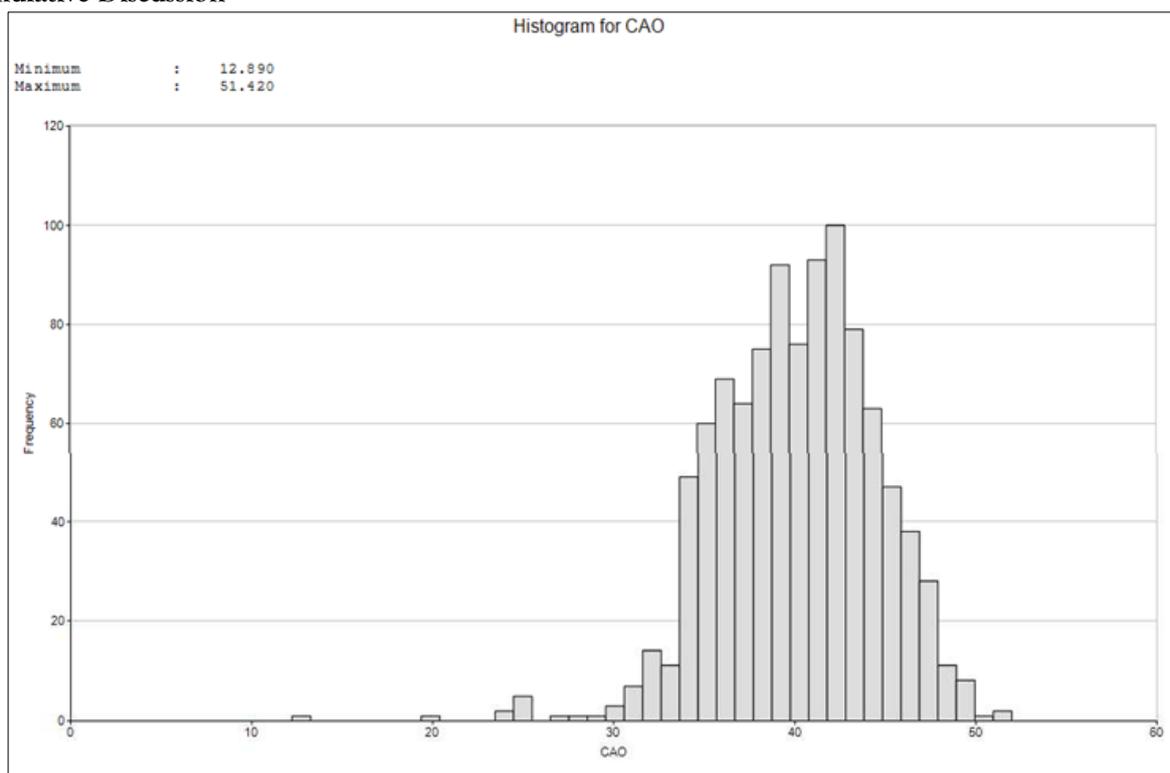


Figure 16 (a): Frequency distribution of CaO values within ore (limestone body)

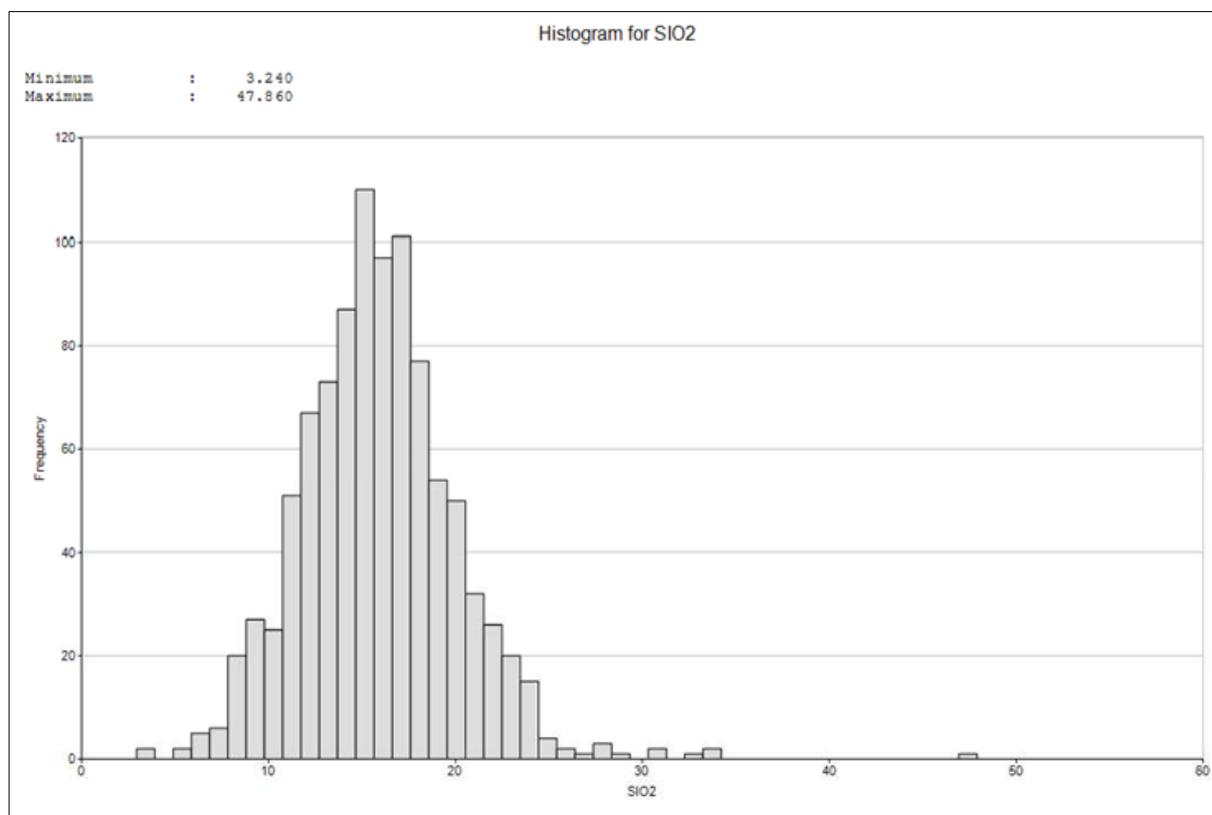


Figure 16 (b): Frequency Distribution of SiO₂ values within ore (limestone body)

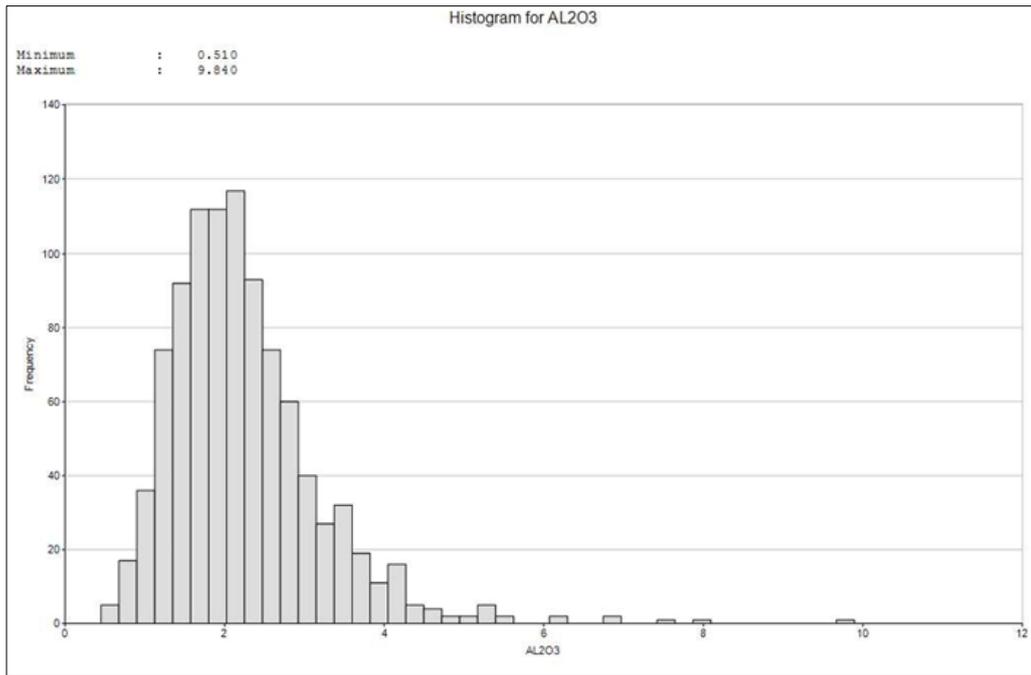


Figure 16 (c): Frequency Distribution of Al_2O_3 values within ore (limestone body)

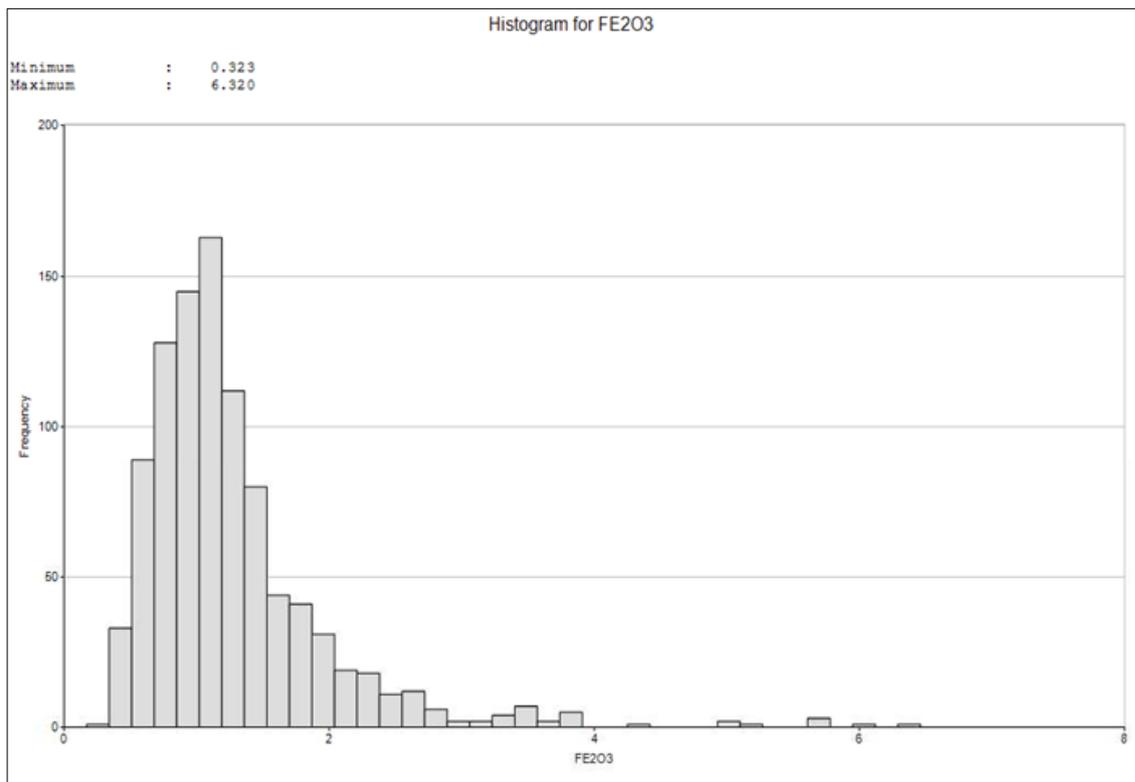


Figure 16 (d): Frequency Distribution of Fe_2O_3 values within ore (limestone body)

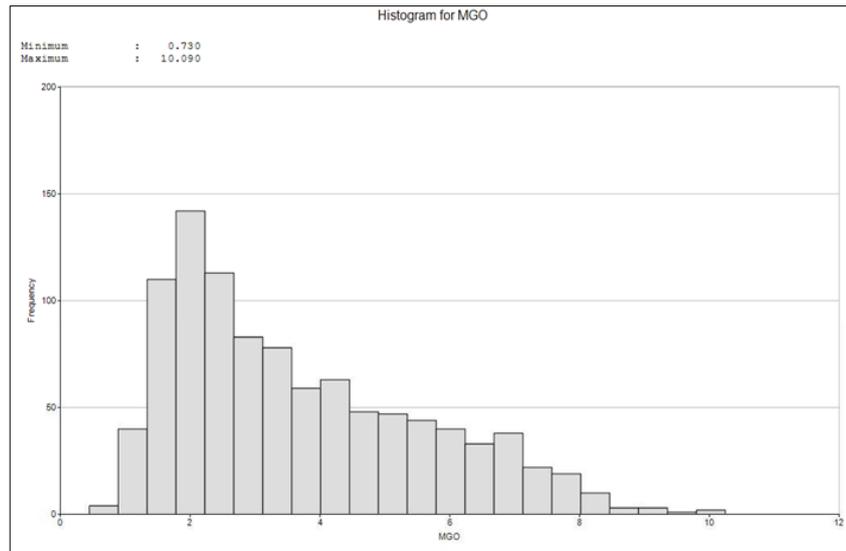


Figure 16 (e): Frequency Distribution of MgO values within ore (limestone body)

Table 3: Statistics on samples within interpreted orebody (> 34% CaO)

FIEL D	NSAMPL ES	MIN	MA X	RANG E	MEA N	VARIA NCE	STAND DEV	STAND ERR	SKEW NESS	KURT OSIS	GEOM EAN
CaO	932	12.89	51.42	38.53	40.02	24.88	4.99	0.16	-0.9	2.76	39.66
Fe ₂ O ₃	900	0.32	7.69	7.37	1.25	0.57	0.75	0.03	2.59	11.51	1.09
Al ₂ O ₃	902	0.51	10.21	9.7	2.24	1.33	1.15	0.04	2.43	10.81	2.02
MgO	932	0.73	10.09	9.36	3.66	3.9	1.98	0.06	0.77	-0.33	3.15
SiO ₂	902	3.24	47.86	44.62	15.9	22.2	4.71	0.16	1.13	5.01	15.22

Statistical analysis has been carried out considering only the samples within the mineralized body above a cutoff grade of 34% CaO. The statistical parameters have been calculated for all the radicals. From the table 4, it can be seen that the average grade of the deposit is 40.02% CaO, 15.9% SiO₂, 3.66% MgO, 1.25% Fe₂O₃ and 2.24% Al₂O₃, for limestone body where CaO > 34%. Histograms have been generated for all the radicals to know their distribution pattern which helps in identifying the presence of outliers and removing them for better estimations. It can be seen from the distribution of CaO, SiO₂, Fe₂O₃, Al₂O₃ MgO that these show near normal distributions with CaO showing a negative skewness whereas others show a positive skewness (Figure 16a, 16b, 16c, 16d, 16e and Table 3).

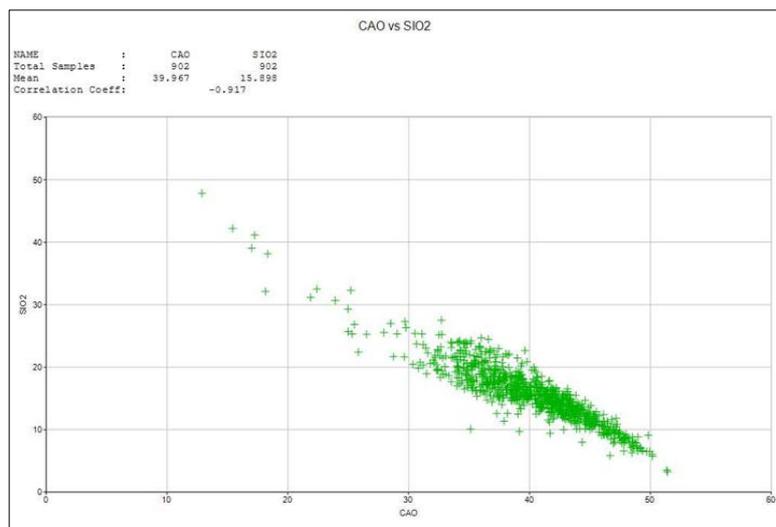


Figure 17 (a): Scatter plot showing relationship between CaO and SiO₂

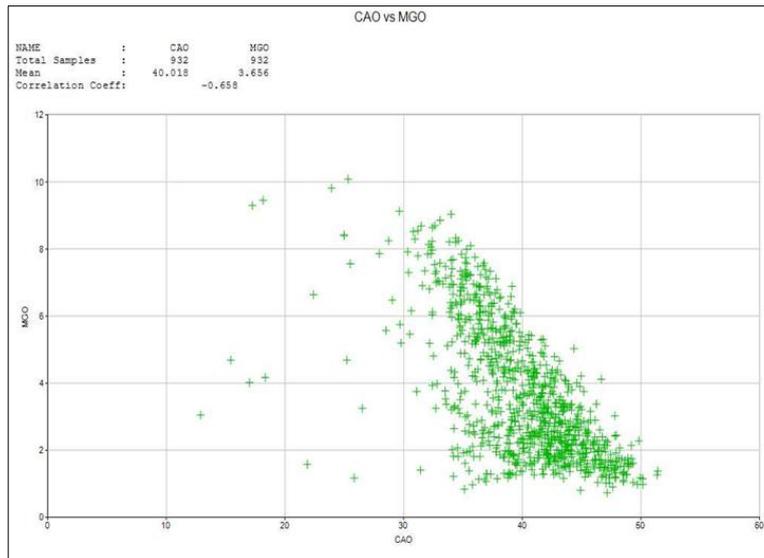


Figure 17 (b): Scatter plot showing relationship between CaO and MgO

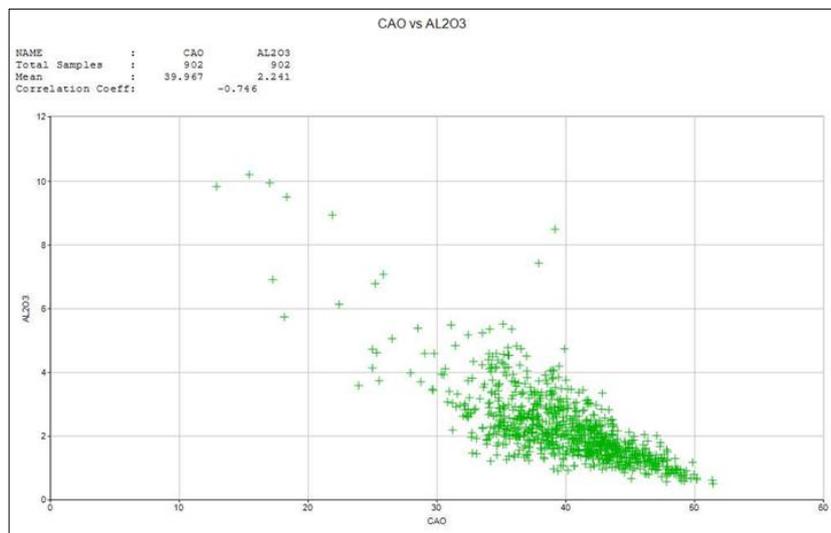


Figure 17 (c): Scatter plot showing relationship between CaO and Al₂O₃

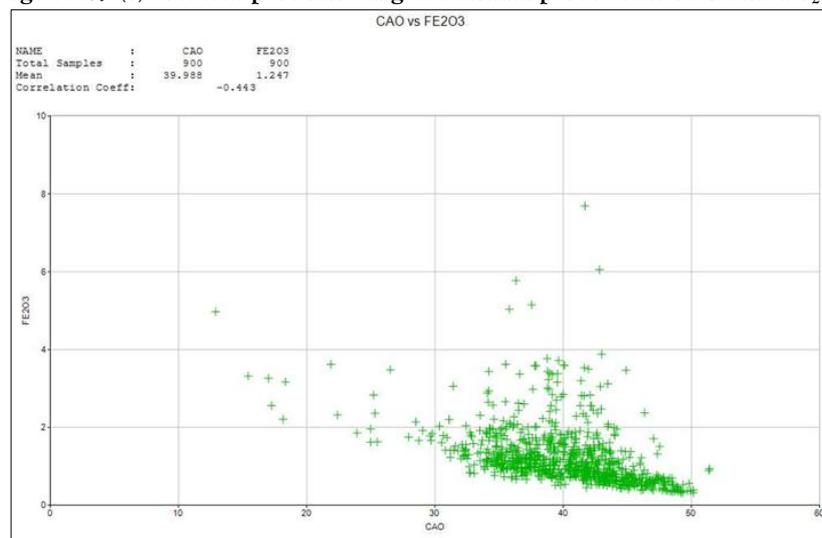


Figure 17 (d): Scatter plot showing relationship between CaO and Fe₂O₃

From the correlation study, it can be inferred that although there exists correlation for CaO vs. SiO₂ (0.9013); rest all the radicals don't have much correlation. It is therefore, can be implied that all the radicals are independent of each other (Figure 17a, 17b, 17c and 17d).

Site Details	No. of BH	Total Depth	CaO	Fe2O3	Al2O3	MgO	SiO2	LSF	Total Depth	CaO	Fe2O3	Al2O3	MgO	SiO2	LSF
Salaiya Deposit	30	101.90	41.29	1.19	2.27	3.04	14.44	94.08	151.95	37.72	1.45	2.63	4.29	17.89	69.69
Sadhera Deposit	82	2078.90	44.77	0.58	1.08	3.45	7.77	191.35	2318.21	42.42	0.70	1.51	3.88	10.22	137.47

Table 4: Quality variation between present feeding and considering IBM Threshold Value in Salaiya and Sadhera Deposit

The comparison of reserve calculation shows significant differences between present and modified beneficiation methods. For Salaiya mines with current reserves calculated at 10.20 million tonnes under the current raw mix calculation reaches upto to 15.20 million tonnes after applying the modified method. The modified beneficiation method represents a substantial 49% increase indicating towards improvised quality criteria, extended mining limits, or inclusion of low-grade zones earlier ignored in the mining operations. The modified LSF of 149% indicates a comprehensive reevaluation of the resource potential, with possible incorporation of improved updated economic factors. While for Sadhera mines with current reserves calculated at 20.78 million tonnes under the current raw mix calculation reaches upto to 23.18 million tonnes after applying the modified method. The modified beneficiation method represents a substantial 12% increase with the modified LSF of 112%.

5. DISCUSSION

The borehole analysis conducted in Maihar District offered crucial insights regarding the depth, thickness, and quality of limestone deposits. Core samples from multiple boreholes when subjected to examine the calcium carbonate (CaCO₃) content, presence of impurities, and stratigraphic variations across different locations consistent limestone bands with varying grades including high-grade and low-grade limestone were found emphasizing the need for selective mining and beneficiation techniques. Such analysis plays a vital role in guiding efficient extraction planning, optimizing resource utilization, and ensuring sustainable mining operations in the region.

Table 5: Resources Calculation

	No. of Bore holes analysed	Assumption – BH Grid 200 X 200 and Bulk Density 2.5		
		Reserves (MT) Calculation @Present Raw Mix	Reserves (MT) Calculation @Modified Raw Mix	% Increased
Salaiya Lst. Mines	30	10190000	15195000	149%
Sadhera Lst. Mines	82	207890000	231821000	112%
Wt. Average	112	873932748.7	1089494149	125%

In the modified methodology the Lime Saturation Factor (LSF) has significantly reduced from 191.35 to 137.47, which is good for manufacturing clinker quality in cement production. These changes suggest the necessity of careful blending and beneficiation strategies to maintain industrial standards while optimizing limestone utilization. The analysis of limestone quality for Salaiya mine exhibits a decline in CaO (Calcium Oxide) content from 41.29% to 37.72% when reaching the threshold value demonstrating a reduction in high-grade material. Meanwhile, MgO (Magnesium Oxide) content shows an increase from 3.04% to 4.29%. Additionally, the Lime Saturation Factor (LSF) also shows a significant drop from 94.08 to 69.69 impacting the overall suitability of the limestone for high-quality cement manufacturing. The cumulative analysis of limestone deposits at Salaiya and Sadhera in Maihar District highlights significant variations in chemical composition, resource estimation, and industrial suitability. Borehole data and exploration studies confirm a 25% increase in estimation of both low-

and high-grade limestone resources. The CaO content shows a declining trend from 44.77% to 42.42% in Sadhera and from 41.29% to 37.72% in Salaiya as mining progresses toward the threshold values. Similarly, MgO levels have increased in both deposits require proper blending to meet cement industry standards.

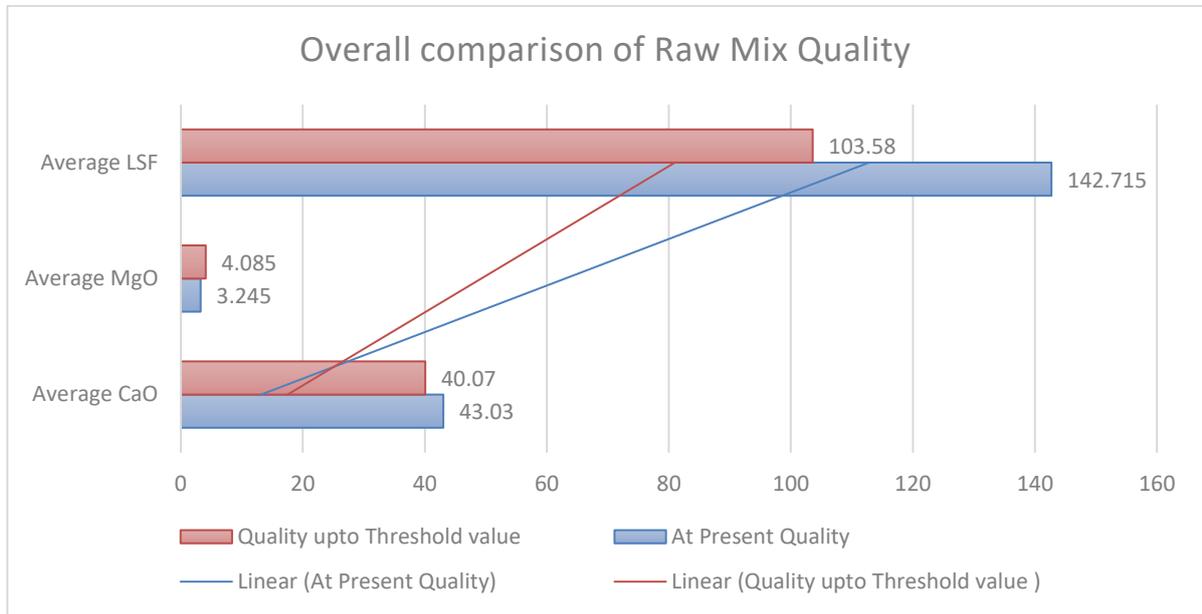


Figure 18: Graphical representation showing the Overall comparison of Raw Mix Quality

The application of IBM threshold parameters establishes a systematic framework for quality control while optimizing the resource utilization. The minimum CaO threshold at 34% makes sure that all raw materials employed in the cement production are economically viable while the 5% MgO limit makes sure that no such material is included in the production process that would compromise the product quality. Several boreholes at the selected sites exhibit the threshold-based classification wherein the currently employed methodology has been unreasonably conservative while resource estimation. For instance, the borehole 21 extending between depths 37.25 to 47.25 meters with CaO content at 40.16% represents one such borehole with substantially enhanced resource recovery. Also, borehole 80 extending between depths 47.50 to 62.50 meters with CaO content at 40.27% indicates towards deep seated unutilized raw material with desired threshold criteria that can be extracted employing the sustainable resource exploitation methodologies.

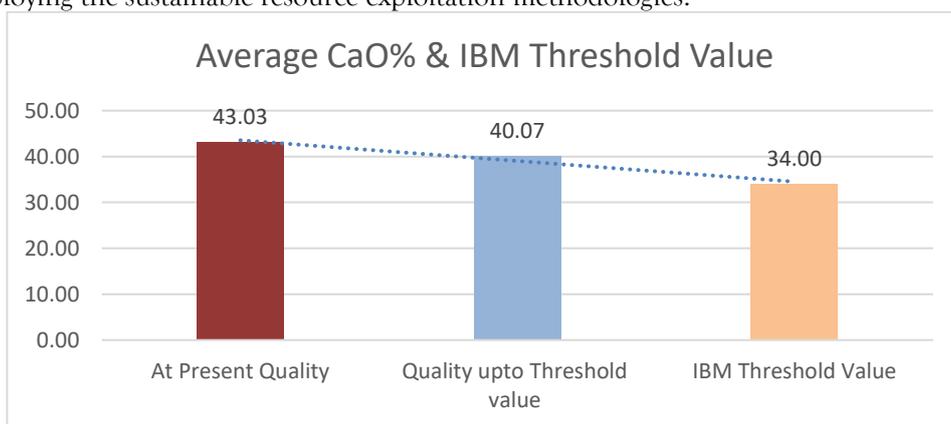


Figure 19: Graphical representation showing the Comparison of CaO% with IBM Threshold Value

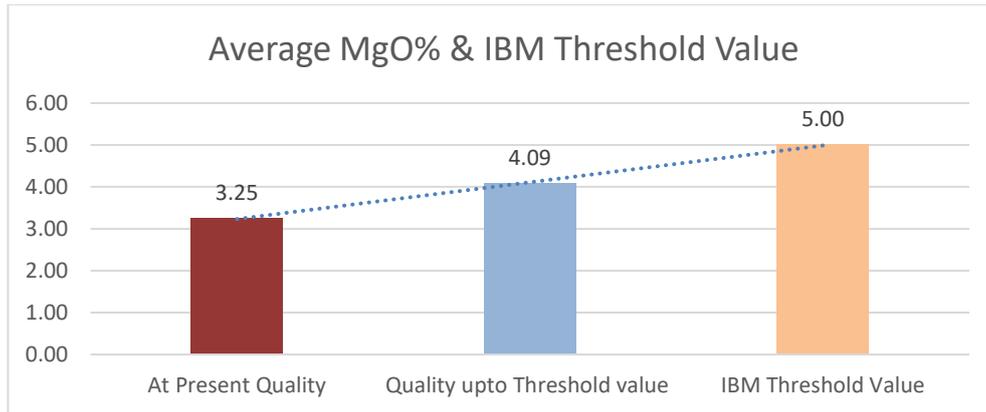


Figure 20: Graphical representation showing the Comparison of MgO% with IBM Threshold Value.

The weighted CaO content of 42.44% as proposed in the modified methodology significantly exceeds the 34% minimum threshold offering operational flexibility in blending the lower grade raw material with the higher-grade supreme quality raw material to optimize the overall product quality. This modified approach enables optimized resource recovery while the planning the mining operations by employing the strategic blending methods. The management of MgO content offers opportunities as well as challenges to utilize the raw material while adhering to the threshold framework (Dixit and Mishra, 2024). Although the 3.87% overall weighted average lies within the accepted limits but the deposits of high MgO content require careful mining operations to ensure prevention of contamination of the low MgO content zones while resource extraction. In such scenarios, overall resource utilization and maintenance of product quality can be obtained by strategic mining sequences separating the high MgO zones for particular utility and blending of the low and high grade MgO deposits. The graphical representation of production vs. overburden is represented in figure 22. Stripping Ratio also increased considering First band limestone is calculated (S/R 1: 0.11) and Stripping Ratio considering Interburden with Second Band Limestone is calculated (S/R 1: 0.15). The extraction of minerals from the second band mining can increase in mineral extraction from 12% to 49%.

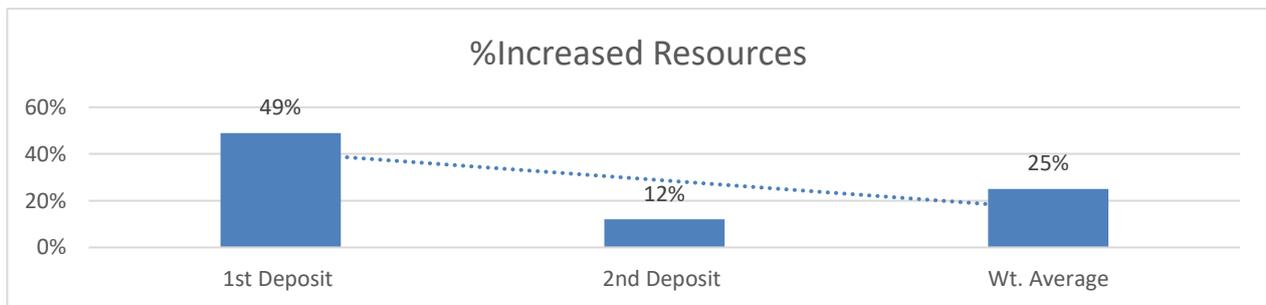


Figure 21: Showing percentage increased in resources

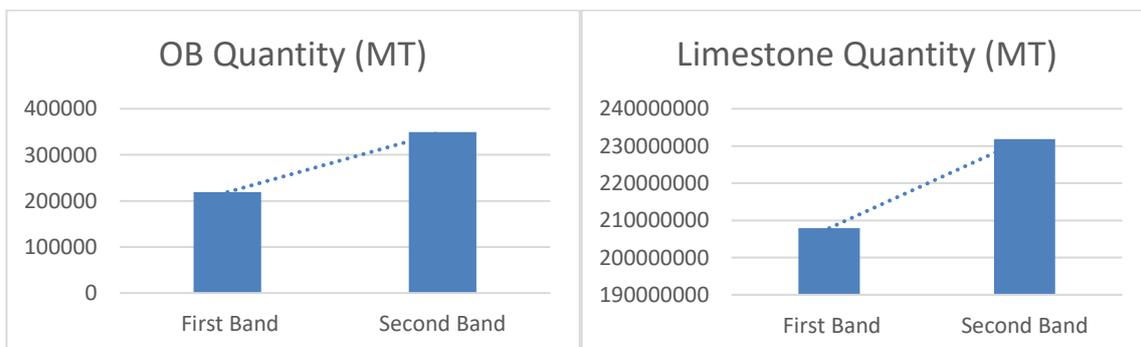


Figure 22: Showing the trend of increasing OB and Limestone from First Band to Second band

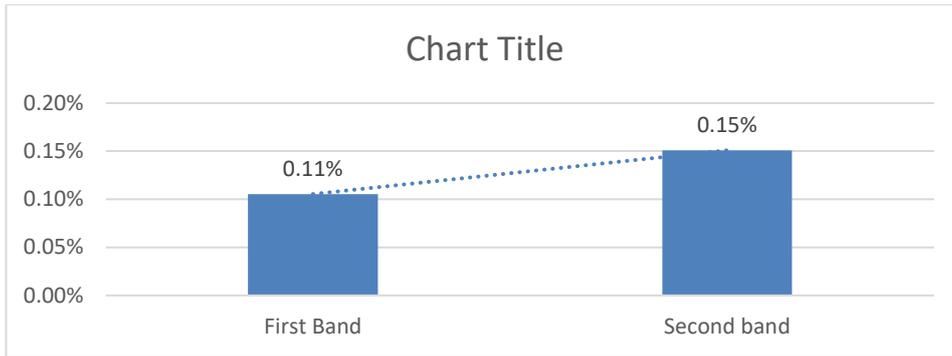


Figure 23: Showing the percentage increasing of Stripping Ratio

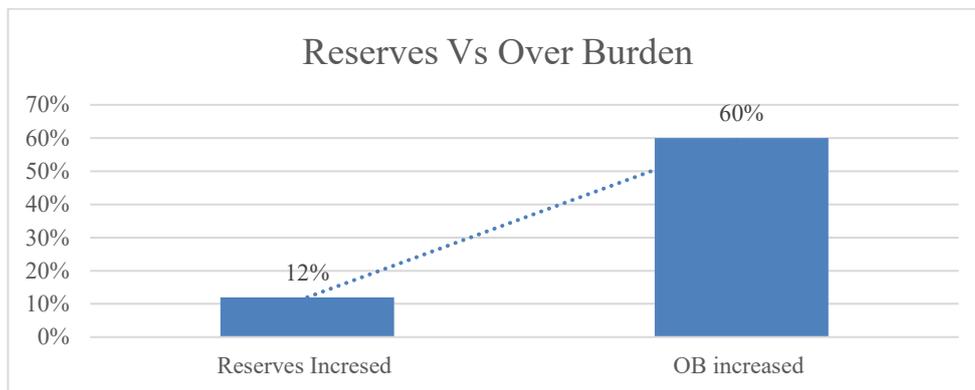


Figure 24: Showing the Increasing of reserves and Over Burden

The current study divulges that the limestone resource estimation in Maihar District has increased by 25%, highlighting a noteworthy enhancement in the available reserves. This enhancement in resource estimation is attributed to advanced exploration techniques, better geological assessments, and the inclusion of previously overlooked low-grade limestone deposits (Dixit and Mishra, 2025).

6. CONCLUSION

Limestone deposits are vital natural resources with significant industrial applications, particularly in cement manufacturing, steel production, construction, and agriculture. As a key raw material, limestone plays a crucial role in infrastructure development and economic growth. The study reveals substantial variability in the properties of limestone such as thickness, grade and depth of deposit with prominent occurrence of banded limestone consisting bands of low- and high-grade deposits. The study particularly identifies industrial utility of deep seated second band limestone which is usually underutilized.

The study confirms that the CaO (Calcium Oxide) content decreases from 43.03% to 40.07% but it is more than the prescribed IBM threshold value and quality in terms of MgO will increase from 3.25% to 4.09% but it is less the prescribed IBM threshold value. To address these variations, blending techniques play a crucial role in maintaining consistency and optimizing limestone utilization. By mixing high-grade and low-grade limestone in appropriate proportions, industries can achieve the required CaO, MgO, and LSF levels to meet cement manufacturing standards. Advanced homogenization techniques, stockpile management, and online analyzers help ensure that the final raw mix remains within permissible industrial limits. The study also confirms that, when compared to IBM Threshold Values, the limestone quality parameters remain within acceptable limits, supporting its continued use in cement and related industries. The inclusion of marginal limestone deposits along with the revised evaluation techniques and blending methodologies offers an overall increase of 25% mineral recovery across both the mining sites. This enhancement of mineral utility ensures not only longevity of the mine life but also results in significant reduction in overburden and inter-burden waste. The findings of this study emphasize the importance of selective mining, proper blending, and sustainable extraction practices to maximize resource efficiency while minimizing environmental impact. The increasing presence of low-grade limestone highlights the need for improved processing techniques to enhance its usability.

Statements and Declarations

Author Contributions

The research article is work of Nitya Kishore Dixit (NKD) under the supervisions of Bhupendra K. Mishra (BKM). Material preparation, field data collection and data analysis were performed by NKD with supervision of BKM. The research idea was proposed by BKM and first draft of manuscript was prepared by NKD and several improvements and revision were done by BKM and Prem Kumar (PK). Pukhraj Nenival and Jaya Rai reviewed and improved it.

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Data Availability: The raw data used for processing can be made available by the first author NKD on request to his email: nitya.dixit@birlacorp.com

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