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Geochemical characterisation of soil using XRF: Implication for geotechnical properties

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Abstract: This study investigates the geochemical and geotechnical properties of soils from Uwelu, Benin City to assess their engineering relevance. Samples from two sites underwent tests including specific gravity, sieve analysis, Atterberg limits, compaction, and California Bearing Ratio (CBR), following ASTM and AASHTO standards. X-ray fluorescence (XRF) was used to determine the presence of major oxides and trace elements. The soils, classified as A-2-4 and A-2-6 by AASHTO, had specific gravities of 2.55 and 2.54. The optimum moisture content was 10%, with Maximum Dry Densities (MDD) of 2.01 and 2.06 g/cm³. CBR results showed higher strength in unsoaked samples (20.11%, 6.38%) than soaked ones (9.69%, 3.24%). SiO_2 dominated the geochemistry (57.33%, 48.36%), with notable Al_2O_3 and Fe_2O_3. The findings emphasize the value of integrating geochemical and geotechnical analyses in construction.

Key words: XRF, geochemical characterisation, geotechnical test, Atterberg's limit, CBR

Geokemijska karakterizacija tla pomoću XRF-a: Implikacije za geotehnička svojstva

Sažetak: Ova studija istražuje geokemijska i geotehnička svojstva tla iz Uwelua, Benin City, Nigerija kako bi se procijenio njihov inženjerski značaj. Uzorci s dvije lokacije podvrgnuti su ispitivanjima kao što su specifična težina, određivanje granulometrijskog sastava prosijavanjem, Atterbergove granice, zbijanje i kalifornijski indeks nosivosti (CBR), u skladu s ASTM i AASHTO standardima. Za određivanje prisutnosti glavnih oksida i elemenata u tragovima korištena je rendgenska fluorescencija (XRF). Tla su, prema AASHTO klasifikaciji, označena kao A-2-4 i A-2-6, sa specifičnim težinama od 2,55 i 2,54. Optimalni sadržaj vlage bio je 10%, a maksimalna zapreminska težina u suhom stanju 2,01 i 2,06 g/cm³. Rezultati CBR-a su pokazali veću čvrstoću u nenatopljenim uzorcima (20,11%, 6,38%) u odnosu na natopljene (9,69%, 3,24%). Geokemijskim sastavom dominirao je SiO_2 (57,33%, 48,36%), uz značajan udio Al_2O_3 i Fe_2O_3. Nalazi naglašavaju važnost kombiniranja geokemijskih i geotehničkih analiza u građevinarstvu.

Ključne riječi: XRF, geokemijska karakterizacija, geotehničko ispitivanje, Atterbergove granice, CBR

1. INTRODUCTION

Soil is a complex and heterogeneous substance that is fundamental to geotechnical engineering, environmental research, and construction practices. Comprehending its properties is crucial for forecasting and enhancing its performance under diverse environmental and load conditions. Historically, geotechnical soil characterisation has depended on physical and mechanical testing techniques to ascertain parameters including shear strength, compaction, permeability, and compressibility. Nonetheless, these methods frequently neglect the chemical and mineralogical composition of soils, which can substantially affect their geotechnical properties [1,2]. Integrating geochemical characterisation into soil studies has become essential for achieving a comprehensive understanding of soil behaviour.

X-ray fluorescence (XRF) spectroscopy has developed into a potent, non-destructive analytical method for geochemical characterisation. XRF facilitates the swift and precise determination of elemental composition, allowing researchers to identify and quantify major, minor, and trace elements in soil samples [3,4]. This data is crucial for correlating geochemical properties with physical and mechanical behaviour, as elements such as silica, aluminium, iron, and calcium frequently determine soil's mineralogical composition, weathering processes, and reactivity [5]. The efficiency, accuracy, and portability of contemporary XRF instruments render them appropriate for both laboratory and field applications, thereby expanding their utility in soil research [6].

The interaction between geochemical and geotechnical properties has significant implications. The presence of reactive minerals, such as montmorillonite or illite-rich clays, can substantially influence the swelling, shrinkage, and shear strength characteristics of soil [7,8]. Likewise, fluctuations in the concentrations of oxides, salts, or organic matter affect soil compaction properties, permeability, and erosion susceptibility [9]. A systematic geochemical analysis can therefore yield insights into soil formation, stability, and appropriateness for particular engineering applications. Furthermore, comprehending the geochemical characteristics of soil is essential for tackling issues associated with construction on problematic soils, including expansive clays or collapsable loess [10].

Recent advancements in soil characterisation highlight the amalgamation of geochemical methods with conventional geotechnical testing. Interdisciplinary approaches are crucial for addressing contemporary engineering challenges, such as sustainable construction practices, waste management, and the development of climate-resilient infrastructure [11]. Utilising geochemical data acquired via XRF, researchers can enhance predictive models and create novel soil stabilisation techniques customised to the distinct mineralogical and chemical characteristics of the soil [12]. This integration also offers potential for improving soil management strategies in agriculture, mining, and environmental remediation [13].

This study seeks to investigate the utilisation of XRF spectroscopy for the geochemical characterisation of soils and assess its implications for geotechnical properties. Through the examination of the elemental composition of diverse soil types, we aim to identify correlations between their geochemical and geotechnical properties, thus enhancing the overall comprehension of soil behaviour. Such insights can guide the design and execution of engineering solutions that are efficient and sustainable. This article aims to emphasise the significance of integrating geochemical and geotechnical analyses, promoting a transformative change in soil research methodologies and applications.

2. REVIEW OF LITERATURE

Providing new insights into the relationship between soil composition and its engineering behaviour, the geochemical characterisation of soil has emerged as a cornerstone of geotechnical research. This is because it offers new insights into the relationship. Because of their accuracy, speed, and capacity to analyse soil samples in a non-destructive manner, geochemical techniques, in particular X-ray fluorescence (XRF) spectroscopy, have become increasingly popular in recent years. This literature review provides a synthesis of the contributions made by recent scholarly works, with a particular emphasis on developments in XRF applications, the interaction between geochemical and geotechnical properties, and the implications for engineering practices from these developments.

Over the course of the last ten years, XRF spectroscopy has undergone significant development, becoming the method of choice for geochemical soil analytical purposes. The capability of XRF to detect major, minor, and trace elements in soil was highlighted by Smith et al. [3]. This ability makes XRF an ideal tool for researching a wide variety of soil compositions. A review of recent developments in portable XRF (pXRF) devices was conducted by Zhao et al. [4], who highlighted the effectiveness of these devices in field studies for the purpose of rapid soil characterisation. In-situ analyses are made possible by these portable tools, which allow for the provision of immediate data on elemental composition. Chang et al. [6] provided additional evidence that pXRF is becoming increasingly reliable in terms of quantifying oxides and minerals that are essential to comprehending the behaviour of soil. These oxides and minerals include silica, alumina, and iron minerals.

The use of X-ray diffraction (XRF) in multi-element analysis was investigated by Liang et al. [5], who highlighted the usefulness of XRF in establishing a connection between geochemical properties and engineering parameters such as cohesion and internal friction angle. This was supplemented by Kumar et al. [9], who used XRF to investigate the influence of elemental concentrations on soil compaction and permeability, thereby determining critical thresholds for the suitability of the soil for construction. The findings of these studies collectively highlight the transformative potential of XRF in terms of bridging the gap between soil analyses conducted in a laboratory and those conducted on-site.

Mineralogy, elemental composition, and organic matter content are examples of geochemical properties that have a significant impact on the geotechnical behaviour of soil. According to the findings of a meta-analysis that was carried out by Bhardwaj and Singh [2] a high silica content improves the stability of soil, whereas reactive minerals such as montmorillonite contribute to swelling and shrinkage. Wang et al. [7], who investigated expansive soils and found correlations between geochemical properties and swelling potential, reported findings that were comparable to those described above.

Zhang et al. [8] conducted an investigation into the impact that oxides and salts have on the cohesion and plasticity of soil. They discovered that increased concentrations of iron oxide led to an increase in soil strength when the soil was saturated. These results were confirmed by Ahmed et al. [1] in tropical soils, highlighting the role that aluminium oxides and iron oxides play in improving the load-bearing capacity of the soil. In addition, Gao et al. [13] conducted research on agricultural soils, focussing on the ways in which organic matter and elemental imbalances can influence the permeability of soil and the amount of nutrients that are retained.

Clay minerals are not the only factors that influence the behaviour of soil; soluble salts also play an important part. Researchers Huang et al. [10] conducted an investigation into salt-affected soils in arid regions. Their findings demonstrated that high salt concentrations decrease soil stability and increase the soil's susceptibility to erosion. The research highlighted the importance of accurate geochemical characterisation in order to address the challenges of soil salinisation that are present in the construction and agricultural industries.

It is becoming increasingly recognised that the integration of geochemical and geotechnical studies is a pathway that can lead to more accurate predictions of the behaviour of soil (especially soil behaviour). The performance of stabilised soils was modelled by Chen et al. [11] using a framework that combined XRF-derived geochemical data with mechanical tests. This framework was used to model the performance of stabilised soils. In a similar manner, Xu and Li [12] utilised XRF data in order to optimise soil stabilisation methods. They demonstrated significant improvements in compressive strength by tailoring lime and cement treatments to the mineralogical composition of the soil.

It is important to note that Patel and Roy [14] investigated the relationship between geochemistry and soil stabilisation. They demonstrated that high concentrations of calcium and silica improve the efficiency of additives such as fly ash and slag. These findings were supported by Liang et al. [5], who emphasised the significance of geochemical properties in the process of developing soil improvement techniques that are both economical and kind to the environment.

The implications of geochemical characterisation extend beyond the realm of geotechnical engineering and have an effect on fields such as agriculture, waste management, and environmental remediation. For example, Smith et al. [3] discussed the role that XRF plays in determining the level of contamination in soil, particularly with regard to heavy metals such as lead and arsenic, which are known to be hazardous to both human health and infrastructure. In studies that were very similar to this one, Zhao et al. [4] highlighted the capability of XRF to locate contamination hotspots and provide information about remediation strategies.

For the purpose of determining whether or not fly ash is suitable for use as a stabilising agent in contaminated soils, Kumar et al. [9] utilised XRF in the field of waste management. According to the results of their investigation, geochemical compatibility is an essential component for effective stabilisation and efficient operation over the long term. Gao et al. [13] demonstrated how XRF could be used to guide the selection of amendments to restore degraded soils in the context of environmental remediation. This was particularly true for soils that had been impacted by industrial pollution specifically.

3. STUDY AREA

Uwelu, situated in Benin City, Edo State, Nigeria, is geographically positioned at a latitude of 6.3861°N and a longitude of 5.5827°E. The region is situated at an elevation of approximately 107 meters (351 feet) above sea level, presenting a moderately elevated landscape [15] in Figure 1.

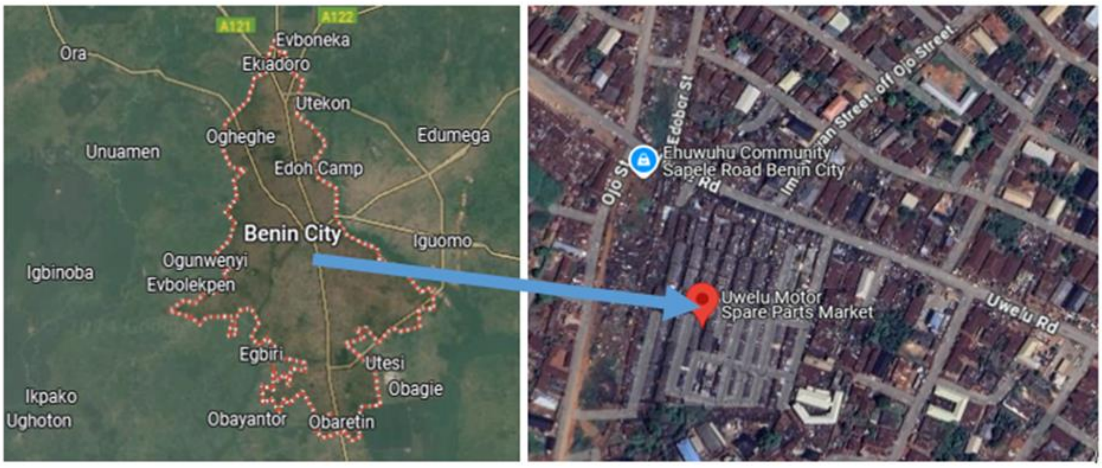

Figure 1. Map of Uwelu Spare Part Market (Google map).

The climate in Uwelu corresponds with that of Benin City, characterised by a tropical wet and dry climate. The region experiences an annual average precipitation of approximately 2,000 to 2,500 mm, characterised by a pronounced rainy season from April to October and a dry season from November to March. The temperature generally fluctuates between 25°C and 35°C annually, with elevated humidity levels, particularly during the rainy season [16].

The geographic and climatic attributes affect numerous activities in Uwelu, particularly its function as a prominent spare parts market in the city. The amalgamation of its central location and accessible infrastructure enhances its status as a nexus for commerce and trade in automotive and machinery components [17].

4. MATERIALS AND METHODS

Laboratory and analytical methods were utilised in the research project in order to investigate the geochemical and geotechnical properties of two soil samples that were collected from Uwelu, which is located in Benin City, Edo State, Nigeria. For the purpose of comprehensively characterising the physical, mechanical, and chemical properties of the soils, these methods were chosen. This allowed for a detailed analysis of the implications that these properties have for engineering and geotechnical applications using these methods.

- Laboratory testing

Standardised procedures, as outlined by ASTM International and the American Association of State Highway and Transportation Officials (AASHTO), were utilised in order to air-dry the samples that were collected and prepare them for analysis. The following examinations were performed on each sample:

Specific gravity test: This test is carried out in order to ascertain the relative density of the soil particles. The pycnometer method was utilised, and according to ASTM D854, it was used. The sieve analysis is a method that is utilised to categorise the soil according to the particle size distribution. In order to classify the soils into the appropriate groups for engineering purposes, the AASHTO classification system was utilised. Third, the Atterberg limits: The liquid and plastic limits were determined in order to calculate the plasticity index, which offers insights into the consistency and behaviour of the soil under different moisture conditions. In order to determine the MDD and the optimal moisture content (OMC), the standard Proctor compaction test was carried out. In order to gain an understanding of the load-bearing capacity of the soil, these parameters are essential. In order to determine the strength of the soil and determine whether or not it is suitable for use in pavement subgrades, the California Bearing Ratio (CBR) was applied to both unsoaked and soaked samples respectively.

- Geochemical analysis

The chemical composition of the soil samples was analysed using X-Ray Fluorescence (XRF) spectroscopy. This method provides precise quantitative data on the elemental composition, including major oxides such as SiO_2, Al_2O_3, Fe_2O_3, and trace elements like MnO, CuO, and ZnO. Sample preparation for XRF involved grinding and pelletizing to ensure homogeneity and reliable results.

5. RESULTS AND DISCUSSION

The geotechnical and geochemical analysis of the two soil samples yields essential information regarding their appropriateness for engineering purposes. This section examines the observed properties, their implications, and the correlations between geotechnical and geochemical characteristics.

- Geotechnical properties

The geotechnical properties results for the test are provided in Appendix 1. The specific gravity values of 2.55 and 2.54 signify soils with low-density mineral compositions. These values correspond with silty and sandy soils, which are less dense than clay-rich soils. These soils are typically appropriate for minor construction endeavours but may necessitate stabilisation for substantial loads.

The AASHTO soil classification system categorises the soils as A-2-4 and A-2-6. These are granular soils containing silty or clayey fines, typically demonstrating favourable drainage properties and moderate load-bearing capacity. A-2-4 soils, characterised by reduced fines content, are more appropriate for subgrade materials than A-2-6 soils, which possess elevated clay content, adversely affecting their stability under load.

MDD values of 2.01 g/cm³ and 2.06 g/cm³, along with optimum moisture content (OMC) values of 10%, demonstrate favourable compaction properties. Soils exhibiting elevated MDD generally provide enhanced stability and strength, rendering the second soil marginally more advantageous for structural support.

The plasticity index (PI) values of 3.1% and 14.1% indicate significant variations in soil plasticity. The initial soil exhibits non-plastic to low-plastic characteristics, indicating enhanced workability and reduced vulnerability to volumetric alterations. The elevated plasticity index of the second soil signifies a greater clay content, potentially resulting in enhanced shrink-swell capacity, necessitating prudence in engineering applications.

The CBR values indicate substantial disparities in the bearing capacity of the two soils. Under unsoaked conditions, the values are 20.11% and 6.38%; however, under soaked conditions, they decrease to 9.69% and 3.24%. The elevated CBR of the initial soil signifies superior load-bearing capacity, particularly in arid conditions. The significant decrease in CBR under saturated conditions indicates that both soils are susceptible to moisture, with the second soil demonstrating heightened sensitivity.

- Geochemical properties

The XRF results offer comprehensive insights into the elemental composition of the soils, which directly affect their geotechnical properties (Appendix 2). SiO_2 (Silica): Soil 1 contains 57.33% silica, whereas Soil 2 contains 48.36%. Elevated silica content correlates with enhanced stability and reduced reactivity, rendering Soil 1 more advantageous for engineering applications.

Al_2O_3 (Alumina): Soil 1 exhibits a markedly higher alumina content (15.23%) than Soil 2 (5.03%). Elevated alumina concentrations frequently signify an increased abundance of clay minerals, which affect plasticity and water retention. This phenomenon is more evident in Soil 2 owing to additional compositional variations.

The magnesium oxide (MgO) and calcium oxide (CaO) concentrations in Soil 1 (7.02% and 0.34%, respectively) and Soil 2 (1.66% and 4.15%, respectively) underscore variations in soil mineralogy. The elevated CaO content in Soil 2 indicates a propensity for cementation when stabilised with lime or cement. Iron oxide (Fe_2O_3) concentrations are elevated in Soil 2 (16.67%) compared to Soil 1 (12.77%), potentially affecting soil colour and its characteristics in reductive environments.

The concentrations of potassium oxide (K_2O) and sodium oxide (Na_2O) are markedly elevated in Soil 2 (8.13% and 5.21%) compared to Soil 1 (0.21% and 0.54%), suggesting the existence of feldspars or other alkali-rich minerals. This influences the reactivity and shrink-swell capacity of Soil 2.

Phosphorus pentoxide (P_2O_5), titanium dioxide (TiO_2), manganese oxide (MnO), and zinc oxide (ZnO) concentrations are typically low, yet they differ between the two soils. Soil 2 exhibits elevated levels of ZnO (2.19%) and TiO_2 (0.71%), potentially influencing its durability and resistance to chemical weathering.

Cr_2O_5 and CuO: Elevated trace levels of chromium oxide and copper oxide are observed in Soil 2, possibly indicating localised geological variations. These elements may possess restricted direct geotechnical significance but could affect soil chemical stability.

The LOI values are similar, measuring 5.01% for Soil 1 and 5.29% for Soil 2, suggesting comparable quantities of organic matter or volatile constituents. This indicates the existence of moderately weathered soils in both instances.

6. ENGINEERING IMPLICATION

There is a correlation between the higher plasticity index of Soil 2 and its lower silica and higher alumina levels, which indicates that Soil 2 contains a greater proportion of clay minerals. The fact that these characteristics are consistent with its A-2-6 classification suggests that stabilisation is required in order to reduce shrink-swell behaviour among the material.

During the process of compaction, the increased MDD of Soil 2 is most likely attributable to the elevated CaO content of the soil, which encourages better particle packing and densification. On the other hand, the higher alkali content (K2O and Na2O) of the substance may be a factor in the possibility of chemical instability.

It is possible that the higher silica content and lower clay activity of Soil 1 are responsible for its superior CBR, particularly when the soil is found in conditions where it is not soaked. The lower CBR performance of Soil 2 in soaked conditions is a reflection of its susceptibility to water-induced weakening, which is associated with the higher alumina and alkali contents of the soil.

With its higher silica content, low plasticity, and better CBR values, Soil 1 is more suitable for construction activities, particularly as a subbase material. This is because Soil 1 has those characteristics. Soil 2, on the other hand, needs to be stabilised in order to address its high plasticity and low bearing capacity when it is saturated with water.

Because Soil 2 contains a higher concentration of CaO and Fe_2O_3, it is possible that it would respond favourably to lime or cement stabilisation, which would result in an improvement in its engineering properties. Despite the fact that Soil 1 is inherently more stable due to its low reactive oxide content, it could still benefit from a slight stabilisation in areas that are waterlogged.

Due to the fact that their CBR values decrease when they are saturated, both soils require adequate drainage systems in order to maintain their existing performance. For the purpose of preventing degradation, Soil 2 in particular requires careful control of the moisture content.

7. CONCLUSION

This study thoroughly assessed the geotechnical and geochemical characteristics of two soils, highlighting their significance for engineering applications. The findings indicate substantial differences in their behaviour and appropriateness for construction, influenced by their inherent geochemical compositions.

Soil 1 exhibited exceptional geotechnical performance, characterised by a low plasticity index, elevated unsoaked and soaked California Bearing Ratio (CBR) values, and optimal compaction properties. The elevated silica content and diminished alumina concentration signify a prevalence of non-plastic silts and sands, rendering it intrinsically stable under diverse conditions. These properties correspond with its AASHTO classification (A-2-4), highlighting its appropriateness for subbase and base course applications in construction.

In contrast, Soil 2 demonstrated increased plasticity, diminished CBR values, and heightened vulnerability to moisture-related degradation, attributable to its elevated levels of alumina, alkali, and iron oxide. The A-2-6 classification indicates the existence of fine-grained clayey materials that, although difficult for direct application, can be enhanced through stabilisation methods. The high calcium oxide concentration in Soil 2 indicates considerable potential for chemical stabilisation through lime or cement, a method that could markedly improve its load-bearing capacity and diminish its shrink-swell potential.

The research highlights the essential interaction between geochemical and geotechnical characteristics in influencing soil behaviour. XRF analysis was essential in determining elemental compositions that influence engineering properties, providing a swift, accurate, and non-destructive technique for soil characterisation. This integrative approach offers a comprehensive framework for customising soil management and stabilisation strategies to meet specific project needs.

Soil 1 is advised for immediate utilisation in light construction, whereas Soil 2 necessitates stabilisation to comply with engineering standards. The results underscore the necessity of integrating geotechnical testing with geochemical analysis to enhance soil utilisation and guarantee sustainable and dependable infrastructure development.

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APPENDIX 1

MINISTRY OF ROADS AND BRIDGES
CIVIL ENGINEERING LABORATORY
SAMPLE TEST RESULTS

Client:

Job: Research	DATE: 17/05/2024

TEST: SPECIFIC GRAVITY

S/N	POINTS	SPECIFIC GRAVITY
1	1A	2.55
2	1E	2.54

TEST: SIEVE ANALYSIS

S/N	POINTS	Percentage Passing sieve size			AASHTO CLASSIFICATION
		1.18mm	0.425mm	0.075mm	
1	1A	91.65	50.3	17.1	A-2-4
2	1E	90.65	48.25	22.5	A-2-6

TEST: COMPACTION

S/N	POINT	MDD(g/cm3)	OMC(%)
1	1A	2.01	10
2	1E	2.06	10

TEST: ATTERBERG LIMIT

S/N	POINTS	ATTERBERG LIMIT TESTS		
		LL(%)	PL(%)	PI(%)
1	1A	18.8	15.7	3.1
2	1E	26	11.9	14.1

TEST: CALIFORNIA BEARING RATIO

S/N	POINTS	PRESSURE LAYER	UNSOAKED (US)		SOAKED(S)		CBR%
			2.5mm	5.0mm	2.5mm	5.0mm	
1	1A	Bottom	20.42	26.93	10.98	14.80	US-20.11

		Top	15.40	17.69	4.37	8.61	S-9.69
2	1E	Bottom	6.02	8.57	3.60	5.95	US-6.38
		Top	4.13	6.81	1.24	2.15	S-3.24

APPENDIX 2

RESULTS OF ANALYSIS

Sample 01: 1A

S/N	Basic Oxides	Formulae	% Composition
1	Silicon Oxide	SiO_2	57.33
2	Aluminum Oxide	Al_2O_3	15.23
3	Magnesium Oxide	MgO	7.02
4	Calcium Oxide	CaO	0.34
5	Iron Oxide	Fe_2O_3	12.77
6	Potassium Oxide	K_2O	0.21
7	Sodium Oxide	Na_2O	0.54
8	Phosphorus Oxide	P_2O_5	0.12
9	Titanium Oxide	TiO_2	0.04
10	Manganese Oxide	MnO	1.27
11	Zinc Oxide	ZnO	0.06
12	Copper Oxide	CuO	0.04
13	Sulphide	SO_3	0.01
14	Chromium Oxide	Cr_2O_5	0.01
15	Loss of Ignition	LOI	5.01