Diesel Fuel Quality Assessment – Case Study of Tarkwa, Ghana*

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Abstract

This paper considered the quality of diesel fuel used in Tarkwa and its impact on health and the environment when used in mining operations and other commercial purposes. A total of 25 diesel fuel samples were sampled from selected fuel farms and Oil Marketing Companies (OMCs) in Tarkwa over a period of eleven (11) months. These samples were tested to check their quality and compared their conformance with Ghana Standard Authority (GSA) diesel fuel requirement (GS 141: 2022, 5th Edition). Test parameters such as density, viscosity, flash point, water content, total sulphur, total contamination, cetane index and distillation via ASTM and ISO methods were employed to check the quality of diesel fuel used in Tarkwa. The results showed that all 25 samples passed the tests for density, total sulphur, viscosity, cetane index, and distillation conforming to the GS 141:2022. With regards to flashpoint, 8% of diesel samples failed the tests, 4% failed the water content and 32% failed the total contamination tests which is not required in the GS 141:2022. In general, the quality of diesel fuel assessed indicated that diesel fuel used in Tarkwa is good especially those supplied for mining operations.

Keywords: diesel fuel, standard, quality, contamination.

1 Introduction

The advocate for clean and sustainable fuels in recent years requires that conventional fossil fuels meet stringent requirements in many countries in accordance with the sustainable development goals - SDG 7 (Owusu and Marfo, 2023). Diesel fuel is a straight-run product obtained from crude oil distillation and it a high sought-after fuel for automotive and industrial engines due to its better engine characteristics and energy intensity. Diesel fuel is reported to be key in economic development and the standard of living globally (Kwao-Boateng *et al*., 2024; Zamiatina, 2016; Speight, 2015;). Its quality may vary depending on the crude source and the refining process from which it is obtained. There are mostly three grades of diesel fuel; plant, land and marine diesel Fuel. Diesel fuels employed for high speed and load, especially for trucks are the land diesel fuels. Those used for low-medium machineries such as generators and for high speed with moderate loads such as ships are the plant and marine diesel fuel respectively (Zamiatina, 2016; Hsu, 2000). Diesel fuel production over gasoline is reported to be increasing worldwide with high consumption especially in road transportation. Its usage is highly recognised for compression ignition engines due to high efficiency, power output, and high fuel economy of these engines. Nevertheless, these engines emit various pollutants into the environment and their performance may also be affected by the quality of the fuel (Kwao-Boateng *et al.*, 2024; Hao *et al*., 2014). Diesel fuel is consumed by a myriad of sectors in Ghana with transportation in the lead, consuming about 80%. In 2020 the total consumption of diesel fuel was nearly 2,000 kilo-tonnes. The 2023 third-quarter petroleum downstream industry report indicates that 420, 555 metric tonnes of diesel was consumed in Ghana, with the Western Region consuming about 17.4%. It is key to note that majority of this fuel is supplied for mining operations in Tarkwa, a mining town with three major mining companies and its environs (Anon, 2023; Amonoo-Neizer, 2021; Broni-Bediako *et al.*, 2020).

Fuel quality is critical in the performance of vehicles, machinery and processing plants that run on engines. The mining companies just like other major companies in Ghana consume millions of litres of fuels annually for their operations. Some of these fuels are imported into the country and others are refined locally. Refined fuels must meet certain required specifications before they are accepted for consumption by different countries through regulated bodies. There are dire consequences of fuels that do not meet consumer specifications and international standards (Hirota and Kashima, 2020; Stępień and Żółty 2020; Al-Arkawazi, 2019; Boadu 2019). Standards for fuels include the Sulphur content, particulate matter, flash point, moisture contents, etc. Such fuels can be classified as bad, low quality or adulterated. The consequences of using such fuels are high obnoxious emissions to the environment, reduced performance of engines, frequent breakdowns of machinery, increased maintenance cost of machinery and overall cost of operations of such machinery and processing plants. Fuels may meet the required standard at the point of production or of-taker points but may be adulterated

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during transportation before they get to the consumer unknowingly. The challenge that bad fuels, low quality fuels and adulterated fuels pose to companies that use both light and heavy-duty vehicles and processing plants can be devastating and should be avoided at all cost (Anon, 2021; Broni-Bediako *et al*., 2020; Anon, 2012; Kalligeros, 2003; Westbrook, 2000).

Although diesel fuels are known to be mainly sourced from atmospheric and vacuum refinery distillation process, its pool may also be obtained from blending streams of cracking processes. To address issues of the diesel combustion performance, lubricity, emissions to environment, storage stability, fuel cleanliness, etc., there is the need to analyse diesel fuels to determine their operating characteristics, physical and chemical properties (Broni-Bediako *et al*., 2020; Innocent *et al.*, 2013). These properties are also important in determining the quality of the diesel fuel and processes involved are mostly guided by various country standards; The American Society for Testing and Materials (ASTM), National Agency of Petroleum (ANP), European Standards Organisation (EN), Institute of Petroleum (IP) and Ghana Standard Authority GS 141: 2022 (Ulberth-Buchgraber *et al.*, 2021; Santos *et al.*, 2015; Anon, 2012). The following are some of the vital parameters used to assess the quality of diesel and other automotive fuels:

1.1 Diesel Fuel Physicochemical Parameters

Some physical and chemical (physicochemical) properties of a diesel fuel include volatility, storage stability, flow, lubricity, stability, and heating value among others. To determine these properties various parameters are used to monitor the quality and performance of the fuel (Kwao-Boateng *et al*., 2024; Hirota and Kashima, 2020; Broni-Bediako *et al.*, 2020; Innocent *et al.*, 2013; Bolf *et al.*, 2010). Some of these important parameters with their standard methods are discussed below.

1.1.1 Flashpoint

Flashpoint is a minor parameter used to determine the temperature at which the test sample ignites or catches fire with air. For diesel fuel, this parameter is mostly determined using the ASTM D 93-Flashpoint by Pensky-Martens Closed Cup Tester (IP 34). The flash point is the lowest temperature at which the application of the flame causes the vapours above the liquid to ignite (Anon, 2022; Nadkarni, 2020; Anon, 2008).

1.1.2 Viscosity

Viscosity is the measure of fluids resistance to flow. ASTM D 445 (IP 71) is used in determining the viscosity parameter of diesel fuel. This major parameter is important to the flow characteristics of the fuel (Anon, 2022; Nadkarni, 2020; Anon, 2008).

1.1.3 Boiling Range

To determine the volatility of diesel fuels there is the need to determine this parameter. It is mostly known as the fundamental parameter for fuels. This method is guided by ASTM D 86 for determining the initial boiling point (IBP), specified intermediary boiling points, and the final boiling point (FBP) (Anon, 2022; Nadkarni, 2020; Anon, 2008; Budag *et al.*, 2006).

1.1.4 Density

The standard methods for determining density are ASTM D 1298 (IP 160) and ASTM D 4052 (IP 365). The former makes use of the insertion of a hydrometer in the fuel sample for density recordings whereas the latter uses a digital analyser. This major parameter influences the heating value of the fuel (Anon, 2022; Nadkarni, 2020; Anon, 2008; Budag *et al.*, 2006).

1.1.5 Cetane Number

A major parameter of much importance to the ignition quality/knocking effect of diesel fuels in engines is the cetane number. This is the percentage by volume of hexadecane (known as cetane) in a combustible mixture that contains cetane and 1-methylnaphthalene whose ignition properties are similar or match with the fuel that is being tested. It affects emissions, starting and combustion performances. Cetane number of a diesel fuel is determined by comparing its combustion characteristics in a test engine with blends of fuels with known cetane number under standard operating conditions. The test method is governed by ASTM D 613 (IP 41). In the absence of a test engine, the cetane index, which is directly related is used (Anon, 2022; Nadkarni, 2020; Anon, 2008; Budag *et al.*, 2006; Schemme *et al.*, 2017; Kirsis, 2007).

Contaminants in diesel fuels can be classified into three; water, organic and inorganic. These contaminants are analysed based on a set standard to ensure the fuel meets specifications to avoid equipment damage before reaching the end user (Anon, 2017). The presence of water in diesel fuel is known to affect engine performance, cause plugging and corrosion. They may also be a habitat for fungi growth. Water contaminants can be as a result of moisture or condensation in storage facilities. To avoid this, fuel tanks need to be fully filled. The presence of microbes in diesel fuel may cause the production of gels and gums which may settle beneath tanks and spread easily throughout the fuel. They may also affect the stability and quality of the fuel (Anon, 2022; Anon, 2021; Nadkarni, 2020; Anon, 2008).

Broni-Bediako *et al*. (2020), assessed the quality of diesel fuel used in Tarkwa based on three parameters that are density, sulphur content and flash point. A total of 15 samples were selected from oil marketing companies (were analysed with the density values ranging from 820 to 836 kg/m3 (at 15 ºC) and these met the requirement set by Ghana Standard Authority for diesel. 20% of the diesel samples analysed failed to meet the minimum value of 55 °C as stipulated by the GS 141:2017, 4th edition. The results from Broni-Bediako *et al*. (2020) reveal that all 15 samples tested recorded sulphur values higher than the requirement set by GS 141:2017, 4th edition that is 50 ppm. It must however be noted that using three parameters to assess the quality of diesel fuel is not enough. Kwao-Boateng *et al.* (2024), conducted an assessment of diesel fuel quality in the Kumasi metropolis based on five parameters including - sulphur content, density, surface tension, viscosity, and calorific value, which is an improvement on the number of parameters employed by Broni-Bediako *et al*. (2020). This current paper however, presents the findings of diesel quality assessment using eight (8) key testing parameters for diesel fuels as outlined by ISO and Ghana Standard Authority requirements for diesel fuels GS 141:2022, 5th edition. Major fuel testing parameters such as cetane index, total contamination and distillation are introduced to directly ascertain the fuel ignition quality and contamination levels of the sampled fuels. The study used Tarkwa, a prominent mining town which houses three major mining companies in Ghana as a case study.

2 Resources and Methods Used

2.1 Materials

Diesel fuels were sampled from some selected oil marketing companies and fuel tank farms in Tarkwa in accordance with GS 141: 2022, the Ghana Standard Authority. The samples were then tested using ASTM/ISO Methods and the GS 141:2022 – diesel fuel requirement for Ghana was used as a benchmark for analysing the quality of diesel. The diesel fuel testing was conducted in the WearCheck Fuel Laboratory (ISO 9001:2015, ISO 14001:2015 and ISO/IEC 17025:2017 certified lab) and Petroleum Laboratory at the University of Mines and Technology all in Tarkwa. The required protocols were followed during field sampling and laboratory testing to ensure the quality of results obtained.

2.2 ASTM/ISO Methods Used:

Table 1 outlines the method used in testing the diesel fuel samples obtained from the selected fuel farms and oil marketing companies. The summary of testing methods employed in this paper is as follows:

i. Density (ASTM D 4052)

The method involves measuring the mass per unit volume of the sample at a temperature of 15oC. The density of each sample was measured using ANTON PAAR SVM3001. A volume of 2.5 mL of each sample was carefully transferred into the sample compartment of the density meter using a syringe to avoid the formation of bubbles. The density of each sample was then determined automatically and displayed on the screen (Nadkarni, 2020; Rand 2003).

ii. Sulphur (ASTM D 5453)

The RX-360SH determines total sulphur in a petroleum product sample using energy-dispersive X-ray fluorescence (EDXRF). Fuel is directly injected in a sample boat. The sample enters into a high-temperature combustion tube where the sulphur is oxidised to sulphur dioxide SO_2 in an oxygen-rich atmosphere. The fluorescence emitted from the excited SO_2 as it returns to a stable state is detected by a photomultiplier tube and the resulting signal is a measure of the sulphur contained in the sample (Nadkarni, 2020; Rand 2003).

iii. Flashpoint (pensky martens) (ASTM D 93)

Automated Pensky-Martens Closed Cup Flash Point Tester APM-8fc was employed. The sample is heated at a slow, constant rate with continual stirring. A small flame is directed into the cup at regular intervals with simultaneous interruption of stirring. The flash point is the lowest temperature at which the vapour above the sample ignites (Nadkarni, 2020; Rand 2003).

iv. Viscosity (ASTM D 445)

The dynamic viscosity of each sample was measured using ANTON PAAR SVM3001. The test specimen is introduced into the measuring cells, which are at a closely controlled and known temperature. The measuring cell consists of a pair of rotating concentric cylinders and an oscillating U-tube. The dynamic viscosity is determined from the equilibrium rotational speed of the inner cylinder under the influence of the shear stress of the test specimen and an eddy current brake in conjunction with adjustment data. The density is determined by oscillation frequency of the U-tube in conjunction with adjustment data. The kinematic viscosity is calculated by dividing the dynamic viscosity by the density (Nadkarni, 2020; Rand 2003).

v. Cetane Index (ASTM D 976)

Test method for calculated cetane index by four variable equation. Cetane index correlations established between the ASTM cetane number and the density and 10 %, 50 %, and 90 % distillation recovery temperatures of the fuel was used. Equation 1 shows the formula for the four-variable correlation (Nadkarni, 2020; Rand 2003).

vi. Water Content (ASTM D 95)

Water content is determined using Coulometer 899 Karl Fischer (KF) Titrator. In a coulometric KF titration, the iodine is generated from the coulometric Karl-Fisher (KFC) solution. Water in a water or air sensitive solid is determined by heating the sample in an oven at 150 oC to evaporate water which is conveyed to a coulometric Karl Fisher titrator which measures the amount of water evolved. As water is released by the sample it is carried by a constant flow of dry air to the coulometric Karl-Fisher titration cell. An excess of iodine indicates the endpoint of the titration. As the amount of water titrated is proportional to the total current (current x time), the water content is determined from the current required for the titration (Nadkarni, 2020; Rand 2003).

vii. Distillation (ASTM D 86)

A 100-mL sample is distilled automatically using pmd 110 at atmospheric pressure. Thermometer readings and volumes of condensate are systematically recorded, and from these data, the results are calculated and reported as initial boiling point, percent recovery temperatures for the mid values and percent total recovery temperature (Nadkarni, 2020; Rand 2003).

viii. Total Contamination (IP 440)

The total contamination that is the content of undissolved substances is determined using filtration. The sample is filtered through a test membrane using vacuum. A known volume of diesel fuel (800 mL) is filtered through a pre-weighed test membrane filter and the increase in membrane filter mass is weight determined after washing and drying (Nadkarni, 2020; Rand 2003).

3 Results and Discussion

The results for the laboratory analysis of the twenty-five (25) diesel fuel samples obtained from the selected OMCs outlets and fuel farms in Tarkwa are discussed in this section. The results are compared with diesel fuel requirements as stipulated in the GS 141:2022. The possible reasons for non-conformance and the negative impacts on diesel engines, health and environment are discussed.

3.1 Density

Fig. 1 compares the density of all the diesel fuel samples tested against the GS 141:2022 standard. It is required that the density of diesel should be within the range of 0.820 to 0.850 kg/l at 20 ºC. These samples were obtained from the OMCs. Density is an important property of petroleum products and it forms part of product specifications for all fuel standards. This property determines the energy content of the fuel, the denser the fuel, the more power the engine can produce (Nadkarni, 2020; Rand, 2003). It is therefore key that the density of fuels should at least meet the minimum requirement to serve as value for money. Diesel fuels recording density values below the required standard could be an indication of fuel adulteration and or contamination. Diesel contaminated or adulterated with kerosene is capable of reducing the density of diesel (Boadu, 2019; Dzida and Prusakiewicz, 2008). This has the propensity to cause havoc to engines should the level of adulteration or contamination extremely high.

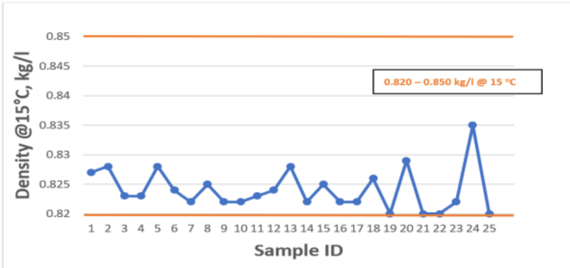

Fig. 1 Density of Diesel Fuel Samples

3.2 Sulphur Content

Fig. 2 indicates sulphur content of the tested diesel fuels and how they compared with the GS 141:2022 standard. Ultralow sulphur diesel fuel is required by many fuel regulatory bodies due to the negative impact of sulphur on human health and the environment when combusted (Kwao-Boateng *et al.*, 2024, Broni-Bediako *et al.*, 2020). Diesel fuel with higher sulphur content produces excess particulate emission pollutants as compared with those of low sulphur content. The impact of high sulphur content on engines is equally unfavourable as it could lead to failed emission control system and corrosion of the liners and pistons when converted to sulphuric acid. High sulphur fuel could lead to the release of the oxides of sulphur gases (SO_x) upon combustion and these gases are among the sources of pollution in the environment and a myriad of health problems such as irritation of the respiratory tract and tract infections. This causes coughing, mucus secretion and exacerbates conditions such as asthma and chronic bronchitis (Oliveira and Lourenço 2021; Boadu 2019). Sulphur is an intrinsic property of crude petroleum and transferred to petroleum products during refining process. 141:2022 that is 50 mg/kg, with the highest sulphur value recorded being 40 mg/kg (sample ID 10).

However, desulphurisation processes are employed during petroleum refining to reduce the sulphur content. It can be seen from Fig. 2 that all the samples tested met the required limit set by GS

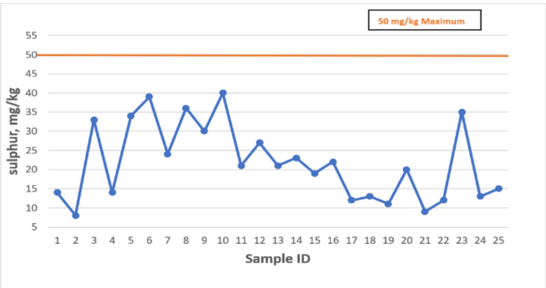

Fig. 2 Sulphur Content of Diesel Fuel Samples

3.3 Flashpoint

The flashpoint values of tested diesel fuel samples as compared with the GS 141:2022 requirement is presented in Fig. 3. The flashpoint temperature of diesel fuel is the minimum temperature at which the fuel will ignite on application of an ignition source (Oliveira and Lourenço, 2021). The flashpoint is one of the physical property indicators for determining fuel quality as an adulterated or contaminated fuel will fail to maintain its flashpoint property. It is also used as safety regulations indicator as it defines flammability and combustibility of fuels especially during shipping and storage (Rand, 2003). Sample ID numbers 6 and 16, representing 8% of the sampled size failed to meet the minimum flashpoint value of 55 ^{o}C. These samples form part of the diesel fuel obtained from the selected OMCs, however all the samples from the fuel farms met the requirement. This is an indication of a possible diesel adulteration or contamination with a more volatile product such as gasoline or kerosene. The flashpoint values obtained are comparable to those recorded by Broni-Bediako *et al.* (2020), when they conducted diesel fuel sample test from selected OMCs in Tarkwa.

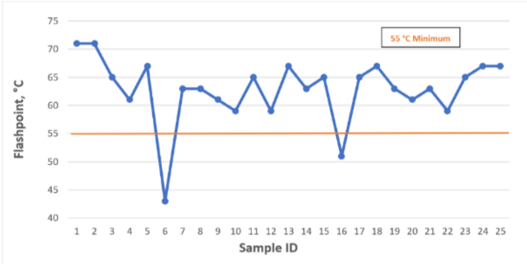

Fig. 3 Flashpoint of Diesel Fuel Samples

3.4 Viscosity

Fig. 4 shows the results obtained for the viscosity of diesel fuel tested. Viscosity is an indication of a fluid's resistance to flow. This therefore has impact on the fuel atomisation and injector lubrication. Fuel viscosity has influence on the shape of fuel spray. The higher the viscosity the poorer the atomisation leading to poor combustion with loss of power and economy and the associated generation of excessive emission. On the other hand, low fuel viscosity can lead to excessive leakage on the injection pump plunger. This tends to affect fuel metering and engine efficiency (Kwao-Boateng *et al.*, 2024; Rand, 2003). All the samples tested had viscosities within the range specified by GS 141:2022, though the viscosities were closer to the lower limit of 2.0 cSt.

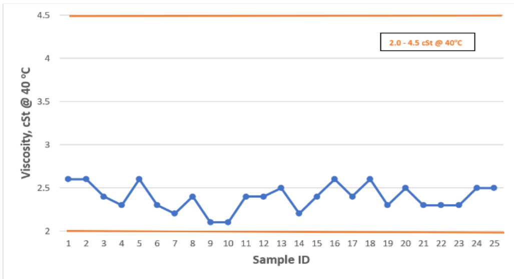

Fig. 4 Viscosity of Diesel Fuel Samples

3.5 Cetane Index (Ignition Quality)

The ignition quality of diesel fuel is measured by its cetane number. This is an indication of the time delay between injection and ignition (Nadkarni, 2020; Rand 2003). The cetane index is directly related to the cetane number and is used to replace cetane number in the absence of a test engine. Fig. 5 shows the results for the cetane index as compared with the requirement as outlined by GS 141:2022. All the samples met the minimum value of 46. When cetane number (index) is too high it will cause the fuel to ignite very close to the injector. This could lead to weak fuel to air ratio which is a precursor to incomplete combustion and soot formation (Nadkarni, 2020).

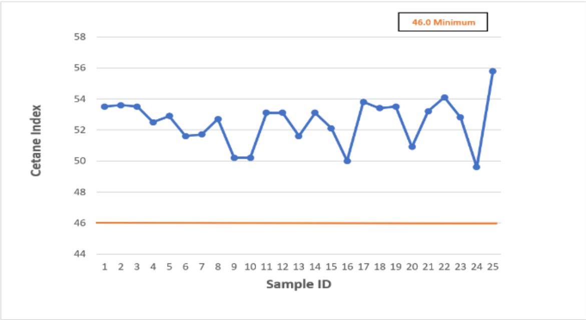

Fig. 5 Cetane Index (Ignition Quality) of Diesel Fuel Samples

3.6 Water Content

Fig. 6 represents the water content of diesel fuel sampled from the selected OMCs and fuel farms in Tarkwa. All the samples satisfied the requirement for water content in diesel fuel of 0.2 vol% (maximum) except sample ID 6. This sample also failed the flashpoint requirement by recording the lowest value of 43 ºC. Water contamination usually arises due to handling, transportation and storage of petroleum products. The water content of petroleum products is useful in predicting the quality and performance characteristics of the produce such as diesel. Water contamination of diesel fuel could lead to phase separation in ethanol and hydrocarbon blends and lead to freezing problems at low temperatures. It also has the propensity to cause corrosion of internal engine parts, sludge formation and filter plugging (Nadkarni, 2020; Rand 2003).

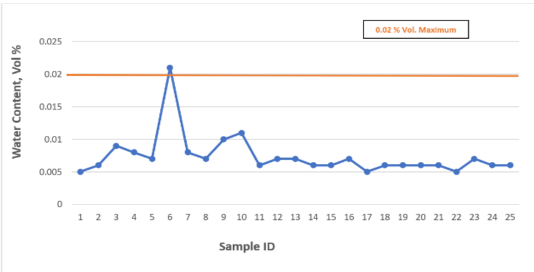

Fig 6 Water Content of Diesel Fuel Samples

3.7 Distillation

Distillation is another parameter for distinguishing between various types of fuel and as such it is used for fuel adulteration and contamination control. Fig. 7 shows the 90% distillation recovery temperature compared with the requirement set by GS 141:2022. It is expected that when diesel is distilled about 90% of its volume should be recovered before the temperature reaches 350 oC. All the 25 samples passed this test. The distillation measures the temperature range over which liquid fuel turns to vapour, that is the volatility. The atomisation of diesel fuel depends on this property and predicts the fuel's ability to start the engine. The fuel's power generation, emissions and deposit formation are also linked to this property (Nadkarni, 2020; Rand 2003).

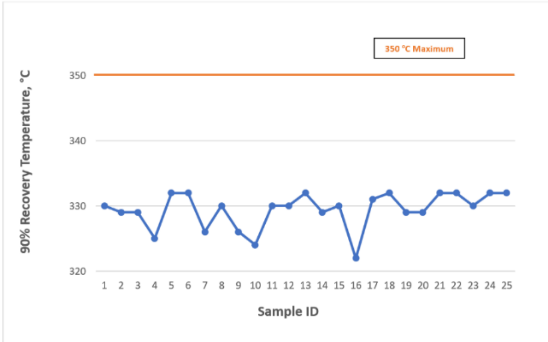

Fig. 7 Distillation of Diesel Fuel Samples

3.8 Total Contamination

Fig. 8 shows the total contamination results for the diesel fuel samples. A total of eight (8) diesel samples representing 32% failed this test by recording values higher than 24 mg/kg as specified in SANS 342 (South African Standard for diesel fuels). The total contamination test is not a requirement of the GS 141:2022, it is mainly an European fuel Standard. However, it is an important parameter for checking the undissolved substance present in diesel fuel. Total contamination is as a result of unintended side-effect of adding Fatty Acid Methyl Esters (FAME) to diesel fuel. When in excess it has the tendency to cause plugging of filters. Total contamination in excess of 36 mg/kg is detrimental to the function automotive diesel engines (Nadkarni, 2020). Combustion of contaminated diesel fuel poses public health problems including aggravating asthma, heart and lung disease, cancer and premature mortality. In 2012, the International Association for Research on Cancer classified diesel exhaust as a known carcinogen to humans.

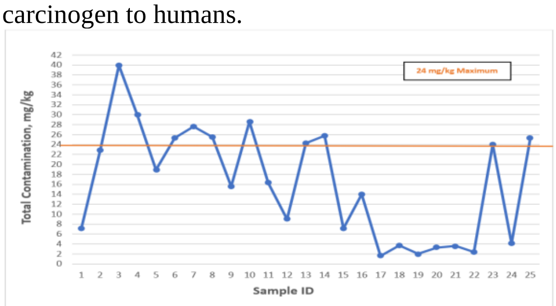

Fig 8 Total Contamination of Diesel Fuel Samples

4 Conclusions

A total of samples twenty-five (25) diesel samples comprised of sixteen (16) from selected fuel farms solely for mining operation and nine (9) from selected Oil Marketing Companies (OMCs) in Tarkwa were tested to ascertain their quality. In all eight (8) parameters of interest via ASTM methods were employed in this paper. The samples' conformance with GS 141:2020, Ghana petroleum and petroleum products - specification for diesel fuel (automotive gas oil) were ascertained. The possible causes for non-conformance and negative impacts were outlined.

Regarding test parameters such as density (ASTM D 4052), total sulphur (ASTM D 5453), viscosity (ASTM D 445), cetane index (ASTM D 976) and distillation (ASTM D 86) all the twenty-five samples passed tests and conformed to the GS 141:2020. 8% of the 25 samples failed to meet the minimum requirement for the flashpoint test (ASTM D 95), 4% of the samples failed the water content test (ASTM D 6304) and as such did not conform to the requirement of GS 141:2022. Regarding the total contamination (IP 440), 32% of the samples failed the test, however it must be noted this is not a requirement of the GS 141:2022.

In general, the diesel samples obtained from the selected fuel farms for mining operations were observed to be of high quality as they conformed with the GS 141:2022 with a few samples from the OMCs failing some of the tests.

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Table 1 ASTM/ISO Methods Employed and Diesel Fuel Requirement in Ghana

(Source: Anon, 2022: Nadkarni, 2020; SANS 342)

SN	Parameter	Apparatus	Method	Diesel Fuel Requirement
1	Density	Anton Paar SVM3001	ASTM D 4052	0.820 – 0.850 kg/m^3 @ 15 °C
2	Total Sulphur	RX-360SH - EDXRF	ASTM D 5453	50 mg/kg Max.
3	Flashpoint	Automated Pensky-Martens Closed Cup Flash Point Tester	ASTM D 93	55 °C Min.
4	Viscosity	Anton Paar SVM3001	ASTM D 445	2.0 – 4.5 cSt @ 40 °C
5	Cetane Index	Calculated	ASTM D 976	46.0 Min.
6	Water Content	Coulometer 899 Karl Fischer (KF) Titrator	ASTM D 95	0.02 Volume % Max.
7	Distillation	Micro Distillation Analyser PMD 110	ASTM D 86	350 °C Max.
8	Total Contamination	Filtration	IP 440	24 mg/kg Max.

$$CCI = 45.2 + (0.0892)(T_{10N}) + [0.131 + (0.901)(B)][T_{50N}] + [0.0523 - (0.420)(B)][T_{90N}] + [0.00049][(T_{10N})^2 - (T_{90N})^2] + (107)(B) + (60)(B)^2$$ **Equation 1**

Where:

CCI = Calculated Cetane Index by Four Variable Equation.

D = Density at 15° C, g/mL determined by Test Methods D1298 or D4052

DN = D – 0.85.

$B = [\ e^{(-3.5)(DN)}] - 1$

T_{10} = 10% recovery temperature, °C, determined by Test Method D86 and corrected to standard barometric pressure,

$T_{10N} = T_{10} - 215$,

T_{50N} = 50% recovery temperature, °C, determined by Test Method D86 and corrected to standard barometric pressure,

$T_{50N} = T_{50} - 260$,

T_{90N} = 90% recovery temperature, °C, determined by Test Method D86 and corrected to standard barometric pressure,

$T_{90N} = T_{90} - 310$.