UNIVERSITI TEKNOLOGI MARA

THE TRIBOLOGICAL EVALUATION OF TREATMENT OIL FOR RESTORING DEGRADED AUTOMATIC TRANSMISSION FLUID (ATF)

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MSc

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ABSTRACT

Automatic Transmission Fluid (ATF) plays a vital role in lubrication, cooling, and ensuring smooth gear shifting in vehicle transmission systems. Typically, ATF is recommended for replacement every 25,000 to 40,000 kilometres, depending on manufacturer specifications and driving conditions. However, ATF can deteriorate much earlier, sometimes before 20,000 kilometres, under extreme operating conditions such as high temperatures, heavy loads, or frequent stop-and-go driving. This early degradation occurs due to base oil oxidation, additive depletion, and accumulation of wear metals, which disrupt boundary film formation and increase friction and wear. This early degradation leads to increased friction, wear, and reduced performance, often resulting in poor gear shifting, abnormal noise, and seal deterioration. To address these issues, treatment oils are introduced as a supplementary additive package. The additive system in ATF, consisting of anti-wear, antioxidant, detergent, dispersant, and extreme-pressure components, plays a critical role in maintaining tribo-film stability and protecting metal surfaces under sliding contact. The treatment is formulated to restore the degraded properties of used ATF by replenishing depleted additives, enhancing lubrication performance, reducing the coefficient of friction, minimizing wear, and improving overall tribological behaviour compared to used ATF. The effectiveness and compatibility of treatment oil in improving tribological performance for used ATFs remain uncertain. This study aims to characterise the physicochemical properties of commercial ATFs and treatment oil, assess the effectiveness of treatment oil in improving the quality of used ATFs, and evaluate the tribological performance of the treated fluids. The treatment involved mixing 4 vol.% of treatment oil into used ATFs, followed by ultrasonication. The samples were analysed according to ASTM standards, which are elemental analysis (ASTM D6595), viscosity and Viscosity Index (VI) measurements (ASTM D445 and D2270), Fourier Transform Infrared Spectroscopy (FTIR) (ASTM E1252), and four-ball tribological tests (ASTM D4172 and D2783). The results shows significant degradation of used ATF in terms of viscosity reduction, additive depletion, and weakened tribological performance due to oxidation and service exposure. Viscosity decreased from 45.6 cSt (fresh ATF) to 36.8 cSt at 40°C and partially recovered to 34.7 cSt after treatment. Elemental analysis revealed depletion of Zn, P, and Ca in the used ATF, while these elements reappeared after treatment. FTIR supported the restoration of functional groups associated with anti-wear and antioxidant additives. Tribological performance improved with up to 18% reduction in friction coefficient and 77% decrease in wear scar diameter compared to untreated used ATF, demonstrating enhanced lubrication and film strength. These findings demonstrate that treatment oil can partially recover degraded ATF by improving boundary film formation, load-carrying capacity, and overall tribological performance, providing new insight into additive-based rejuvenation strategies for used transmission fluids. In general, the treatment oil improved the performance of degraded ATF and could extend fluids last longer.

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TABLE OF CONTENTS

		Page
CONFIRMATION BY PANEL OF EXAMINERS		**ii**
AUTHOR'S DECLARATION		**iii**
ABSTRACT		**iv**
ACKNOWLEDGEMENT		**v**
TABLE OF CONTENTS		**vi**
LIST OF TABLES		**ix**
LIST OF FIGURES		**x**
LIST OF SYMBOLS		**xi**
LIST OF ABBREVIATIONS		**xii**
CHAPTER 1 INTRODUCTION		**1**
1.1	Research Background	1
1.2	Problem Statement	2
1.3	Research Objectives	3
1.4	Significance of Study	3
1.5	Scope and Limitation of Study	4
1.6	Thesis Outline	5
CHAPTER 2 LITERATURE REVIEW		**6**
2.1	Introduction	6
2.2	Fundamentals on Tribology	6
	2.2.1 Friction	6
	2.2.2 Wear	7
	2.2.3 Lubrication	8
2.3	Automatic Transmission Fluid (ATF)	10
	2.3.1 Functions of ATF	11

2.3.2 Properties of ATF 12
2.3.3 Composition of ATFs 13
2.3.4 Additives in ATF 15
2.3.5 Degradation of ATF and Performance Loss 19
2.4 Treatment Oil for ATF 20
2.4.1 Purpose and Composition of Treatment Oils 21
2.4.2 Mechanism of Action in Restoring Used ATF 21
2.4.3 Performance Improvement Reported in Previous Studies 22
2.4.4 Compatibility with Existing ATF Formulations 23
2.4.5 Current Challenges 24
2.4.6 Research Gap 24
2.5 Characteristics of ATF 25
2.5.1 Fundamental Physicochemical Properties of Substance in ATF 26
2.5.2 Tribological Properties of ATF from Other Researchers 31
2.6 Concluding Remarks 32

CHAPTER 3 RESEARCH METHODOLOGY 34
3.1 Introduction 34
3.1.1 Research Flow 34
3.2 Sample Preparation of Fresh ATFs, Used ATFs and Treated ATFs. 35
3.3 Physiochemical Properties Tests 37
3.3.1 Elemental Analysis 38
3.3.2 Viscosity 38
3.3.3 FT-IR Analysis 39
3.4 Tribological Properties Tests 40
3.4.1 Wear Preventive (WP) Measurement 40
3.4.2 Extreme Pressure (EP) Measurement 41
3.5 Concluding Remarks 42

CHAPTER 4 RESULTS AND DISCUSSION **43**

4.1 Introduction 43

4.2 Homogeneity of Used ATFs with Treatment Oil 43

4.3 Physiochemical Properties of Fresh ATFs, Used ATFs and Treated ATFs 44

4.3.1 Composition of Fresh ATFs, Used ATFs and Treated ATFs 44

4.3.2 Viscosity 49

4.3.3 FT-IR Characterization 54

4.4 Tribological Properties of Fresh ATFs, Used ATFs and Treated ATFs 59

4.4.1 Wear Preventive (WP) Measurement 59

4.4.2 Extreme Pressure (EP) Measurement 66

4.5 Concluding Remarks 68

CHAPTER 5 CONCLUSION **69**

5.1 Conclusion 69

5.2 Recommendations 70

REFERENCES **71**

AUTHOR’S PROFILE **82**

LIST OF TABLES

Tables	Title	Page
Table 2.1	Types Of Lubricants	10
Table 2.2	Technical Specifications Of Fresh ATF Samples From Suppliers	12
Table 2.3	The Types Of Additives And Its Function	16
Table 2.4	Roles Of Elements As Additives	18
Table 2.5	Elements Detected By Spectroil Q100 (Source: ASTM International)	27
Table 2.6	The Spectral Location Of The Components.	30
Table 2.7	Summary Of Tribology Findings	32
Table 3.1	Samples Material	36
Table 3.2	ATF Properties Testing	37
Table 3.3	Test Parameters For The WP	41
Table 3.4	Test Parameters For The EP	42
Table 4.1	The Elemental Composition Of The Reference Atfs In Parts Per Million (Ppm).	45
Table 4.2	Type Of Elements Of Samples ATF A And ATF B.	47
Table 4.3	The Atfs Extreme Properties	67

LIST OF FIGURES

Figures	Title	Page
Figure 2.1	(a) Capillary Viscometer (b) Rotational Viscometer (c) Falling Ball Viscometer	28
Figure 2.2	FTIR Spectrum Region	30
Figure 3.1	Flow of Research Methodology	35
Figure 3.2	Process of Making Treated ATFs	36
Figure 3.3	a) Treatment Oil, b) Fresh ATF A_0, c) Used ATF A, d) Treated ATF A_1	37
Figure 3.4	(a) The Spectroil Q100 spectrometer, and (b) Test specimen inside the spectrometer.	38
Figure 3.5	(a) The viscometer bath, and (b) The U-tube inside the viscometer bath	39
Figure 3.6	(a) FTIR Machine, and (b) A schematic diagram of the optical system	39
Figure 3.7	(a) The four-ball wear tester, and (b) the four-ball assembly	41
Figure 4.1	The samples observation of (a) ATF A1 and (b) ATF B1	43
Figure 4.2	Variation of kinematic viscosity at different temperature of fresh ATF samples.	49
Figure 4.3	Viscosity Index (VI) of fresh ATFs samples	51
Figure 4.4	The kinematic viscosity of (a) ATF A and (b) ATF B	52
Figure 4.5	Graph of viscosity index (VI) and kinematic viscosity at 40°C and 100°C of ATF B	53
Figure 4.6	FTIR spectra of fresh ATF samples	55
Figure 4.7	FTIR spectra of ATF A_0, A and A_1 samples	56
Figure 4.8	FTIR spectra of ATF B_0, B and B_1 samples	58
Figure 4.9	The friction coefficient over time of (a) ATF A and (b) ATF B	60
Figure 4.10	The friction coefficient of (a) ATF A and (b) ATF B	61
Figure 4.11	Wear scar of 3 balls of (a) ATF A_0, (b) ATF A and (c) ATF A_1	63
Figure 4.12	Wear scar of 3 balls of (a) ATF B_0, (b) ATF B and (c) ATF B_1	64
Figure 4.13	Average wear scar diameter of (a) ATF A and (b) ATF B	65

LIST OF SYMBOLS

Symbols

A	Surface area
˚C	Degree Celcius
F	Friction force
N	Normal force or normal load. Also used as relative speed (for the Stribeck curve)
V	Volume
μ	Coefficient of friction

LIST OF ABBREVIATIONS

Abbreviations

ASTM	American Society Of Testing Materials
ATF	Automatic Transmission Fluid
$CaCO_3$	Calcium Carbonate
$Ca(OH)_2$	Calcium Hydroxide
EDX	Energy-Dispersive X-Ray
EP	Extreme Pressure
FT-IR	Fourier Transform Infrared
hBN	Hexagonal Boron Nitride
MoS_2	Molybdenum Disulphide
MoDTP	Molybdenum Dithiocarbamate
OEM	Original Equipment Manufacturer
POA	Polyalphaolefins
WP	Wear Preventive
ZDDP	Zinc Dialkyldithiophosphate

CHAPTER 1
INTRODUCTION

1.1 Research Background

Automatic transmission fluid (ATF) is a fluid that lubricates gears, operates the torque converter, and manages brake band friction. ATF is also used in some manual transmissions, transfer cases, and power steering systems. It serves as a hydraulic fluid, protects gears, controls heat, and ensures smooth shifts (Halley et al., 2020; Rizvi, 2003). Modern hydraulic components were developed with the additional goals of boosting machine reliability and technical life, decreasing energy intensity, minimising environmental pollution, and enhancing transmitted power (Kosiba & Petrović, 2018).

The degradation of ATFs over time due to high temperatures, wear, and contamination poses a significant challenge in maintaining vehicle transmission systems, especially when failure occurs earlier than expected. These high temperatures often result from continuous friction between moving parts and heavy operational loads, especially under harsh driving conditions (Farfan-Cabrera et al., 2021a). As ATF degrades, its lubricating and friction-reducing properties diminish, increasing the risk of issues such as vibrations, gearbox noise, and rough shifting (Hoque et al., 2020). These problems accelerate wear on transmission components and reduce overall system performance, ultimately shortening the lifespan of the transmission (Rizvi, 2003). Additionally, prolonged exposure to elevated temperatures can cause gearbox seals to harden or tear prematurely, leading to fluid leaks and further mechanical failure.

The introduction of oil treatments has been suggested as a potential solution to restore or enhance the tribological properties of used ATFs. However, the effectiveness of these treatments remains uncertain (Sabri et al., 2024). It is challenging to evaluate commercial ATFs' suitability for various gearbox systems and operating environments due to the lack of transparency around the formulations and additives used in them. These concerns draw attention to the need for more research into whether oil treatments can extend the lifespan and efficiency of gearbox systems under a variety of circumstances and how it can lessen the problems brought on by ATF degradation, such as wear, noise, and poor performance.

The degradation of ATF and its impact on gearbox performance are the primary challenges. Thus, this study aims to assess the tribological effects of treatment oil in used ATF by evaluating its impact on friction, wear, and lubrication performance. By addressing this issue through oil treatments and investigating its compatibility with various ATF formulations and transmission systems, it will offer useful insights into enhancing transmission efficiency and reliability solutions that can prevent premature wear and improve vehicle transmission performance.

1.2 Problem Statement

ATF are typically prescribed for replacement at intervals of 25,000 to 40,000 kilometres, depending on manufacturer specifications and driving conditions. However, ATFs may degrade prematurely under severe operating conditions such as prolonged high temperatures, oxidative stress, shear loading, contamination, and additive depletion. Among the various degradation mechanisms, oxidation is the primary root cause of ATF deterioration, particularly under severe operating conditions such as elevated temperatures, prolonged service time, and exposure to contaminants. Oxidative degradation leads to additive depletion, viscosity changes, and the formation of acidic and insoluble by-products, which collectively impair the lubricating and protective functions of ATF (Farfan-Cabrera et al., 2021b).

As oxidation progresses, the friction-modifying and anti-wear performance of ATF deteriorates, resulting in rough or delayed gear shifting, increased gearbox noise, and abnormal vibrations (Őri et al., 2023; Peric et al., 2013). These symptoms reflect increased friction and wear at contacting surfaces due to the breakdown of the fluid's protective film. If left unaddressed, oxidation-induced degradation accelerates gear tooth wear and reduces overall transmission efficiency.

In addition to mechanical effects, oxidation significantly affects the chemical compatibility of ATF with elastomeric seals. Oxidized ATF can promote seal hardening, shrinkage, or swelling, leading to fluid leakage, loss of hydraulic pressure, and eventual transmission failure (Farfan-Cabrera et al., 2021b; Holdmeyer, 2024). These consequences further emphasize oxidation as a critical factor governing both mechanical reliability and hydraulic integrity in automatic transmissions.

Oil treatment products have been introduced to mitigate oxidation-related degradation and restore ATF performance. There is a lack of systematic tribological evaluation examining the effectiveness of treatment oils in counteracting oxidation-induced wear and friction in used ATFs, particularly under standardized testing conditions. Existing studies frequently focus on fresh lubricants or general physicochemical changes, offering limited insight into how treatment oils influence tribological behaviour in oxidized ATFs.

The research gap addressed in this study lies in the absence of comprehensive tribological assessment of treatment oils for mitigating oxidation-driven degradation in used ATFs. This study aims to fill this gap by evaluating the physicochemical and tribological properties of fresh, used, and treated ATFs, with particular emphasis on friction, wear, and oxidation-related performance changes.

1.3 Research Objectives

The objectives for this research were:

1. To characterize the physicochemical properties of standard fresh ATF formulations and treatment oil.
2. To assess the physiochemical and role of treatment oil in improving the physicochemical properties of used ATFs.
3. To evaluate the tribological properties and effects of oil treatment in used ATFs.

1.4 Significance of Study

By evaluating the effects of oil treatments on friction, wear, and lubrication performance, this study offers important insights into how well the treatment oil restores and improves the performance of used ATFs. ATFs are necessary for lubrication, cooling, and smooth gear shifting in automatic transmissions; however, fluid deterioration over time may cause problems with performance. This study assesses the physicochemical and tribological characteristics of used and treated ATFs to ascertain whether oil treatments can increase the lifespan of ATFs and enhance gearbox performance. By providing cost-effective maintenance techniques, these findings may help car owners and auto repair shops cut down on the frequency of ATF replacements and overall gearbox repair expenses.

This study expands understanding of the mechanisms underlying ATF degradation and the impact of oil treatments on wear, friction, and extreme pressure situations from the standpoint of tribological and lubrication research. For lubricant manufacturers, knowing how fluid properties change after treatment gives them useful information that helps create better formulations for better gearbox performance. By offering analytical information on fluid-film protection capabilities, viscosity changes, and additive effects, the study also helps to standardise ATF testing.

In addition to applications in industry and research, this study deals with environmental issues. Since used oils contain hazardous components, premature ATF disposal adds to waste production and pollution. This study encourages environmentally friendly automotive fluid management techniques by investigating methods to extend ATF usability. If successful, oil treatments may lessen the need for new ATFs, reducing the negative effects of lubricant manufacturing and disposal on the environment.

Lastly, this study supports regulatory bodies and industry professionals by providing data that could aid in assessing the safety and compatibility of commercially available oil treatments. As proprietary formulations often lack transparency, evaluating their effects on different ATF brands and transmission systems is essential for ensuring optimal vehicle performance. By addressing these uncertainties, this research contributes to the development of better-informed maintenance practices, improved lubricant formulations, and more sustainable solutions in automotive fluid management.

1.5 Scope and Limitation of Study

This study is focused on the evaluation of the effectiveness of oil treatments in used ATFs, analysing its compatibility with various transmission systems, and identifying solutions to enhance gearbox performance and longevity. It encompasses the preparation process of the oil treatment, testing, and analysis. With that purpose, determination of the additive effectiveness is based on a set of test methods. To ensure the feasibility of this study within the time available, the following scope and limitation is defined:

i. The five ATF brands were selected based on its availability in the local market and compliance with Dexron III specifications. Dexron III is a widely used ATF standard that defines essential performance criteria, including friction, oxidation stability, and wear protection. Specific brand names are not disclosed due to confidentiality agreements.
ii. The treatment oil is supplied by JV Auto Lube Sdn. Bhd., Shah Alam, Selangor, with a fixed concentration of 4 vol.% in used ATFs, as per the supplier's recommendation.
iii. The used ATF samples were collected from vehicles operating under normal driving conditions, with an average mileage of 20,000 km before sampling. However, variations in vehicle type, driving habits, and operating temperatures may influence the results.
iv. All experiments were conducted under controlled laboratory conditions, which may not fully replicate real-world operating conditions such as prolonged high-temperature exposure or varying load conditions.
v. The elemental composition of the sampled ATFs was analysed using a Spectro-oil Q100 device, in accordance with the ASTM D6595 standard.
vi. The viscosity of the ATF samples was measured using a capillary viscometer according to the ASTM D445 standard, and the Viscosity Index (VI) was calculated following the ASTM D2270 standard.
vii. The Fourier Transform Infrared Spectrometry (FTIR) was used to identify organic, polymeric, and inorganic materials in the ATFs, following ASTM E1252 standards.
viii. The tribological tests were limited to the four-ball tester, which the evaluation of wear, coefficient of friction (CoF) and extreme pressure, following the ASTM D4172 and ASTM D2783 standards. While the four-ball tester provides valuable insights into wear and friction characteristics, it does not fully replicate the dynamic and complex operating conditions within an actual automatic transmission system.
ix. Potential interactions between different ATF formulations and the treatment oil were not fully explored, which may affect the generalizability of the findings. Additionally, while precautions were taken to prevent contamination, minor variations in sample handling could influence the results.
x. The selection of ATF brands was limited to specific products available in the studied region (Malaysia), which may not fully represent the global ATF market.

xi. The study focuses on ATFs commonly used in a specific market, and results may not directly apply to other climates, vehicle types, or regional formulations.

xii. Due to time constraints, the study does not include long-term field testing under real-world conditions, such as extended mileage evaluations or varying driving environments.

xiii. Proprietary formulations of ATFs or treatment oils might limit the ability to fully characterize and compare their performance, potentially impacting the study's conclusions.

1.6 Thesis Outline

The overview of this research proposal is as follows: Chapter Two provides a review of previous literature on the related topic and field. Chapter Three explains the research methods with the identification of samples and equipment to be used. Results and discussion on the properties of the samples were briefly explained in Chapter Four. Chapter Five concludes the study of this research.

CHAPTER 2
LITERATURE REVIEW

2.1 Introduction

This chapter covers the fundamentals of tribology, grease lubricants and their components, the concept of biodegradability, and the potential of vegetable oils, particularly palm oil, as alternative base oils for bio-grease development. The discussion extends to the processes involved in grease preparation and the standard methods for testing grease properties. Additionally, the chapter reviews past studies related to greases for rail lubrication. Finally, a summary and an identification of research gaps are also provided.

2.2 Fundamentals on Tribology

Tribology is the study of friction, wear, and lubrication, focusing on the interactions between surfaces in relative motion. It examines contact principles and lubrication techniques with the primary goal of reducing friction and wear, thereby enhancing the efficiency and lifespan of mechanical systems (Bhushan & Ko, 2003). Excellent tribological performance not only extends system longevity but also reduces energy consumption, contributing to environmentally sustainable industrial development. According to Torbacke et al., 2014, tribological contact is influenced by a limited set of variables and conditions. Tribology focuses on tribo-systems, which consist of interacting surfaces. In lubricated systems, contact stress can form tribo-films that influence performance. Tribology includes subfields such as tribotronics, bio-tribology, nanotribology, and space tribology, each addressing specific applications (Bhushan & Ko, 2003). When two solid surfaces touch or slide against each other, friction produces heat and raises the local temperature, which can cause wear even at low loads and speeds. Lubrication reduces these effects by forming a fluid film that separates the surfaces, lowering friction and wear. Lubricants also help remove heat, prevent corrosion, and transmit power (Salimon et al., 2010).

2.2.1 Friction

Friction is the force that resists motion when one surface moves over another. It acts along the contact surfaces and can slow down or stop movement. Friction occurs under dry or viscous conditions. In dry contact, friction is classified as static or kinetic: static friction resists the start of motion, while kinetic friction opposes motion after movement begins. These forces arise from microscopic interactions at the contact surfaces. When motion occurs through or along a fluid layer, viscous friction takes place. In this case, resistance depends on the distance between surfaces, relative speed, and fluid properties. In lubricated systems, friction is governed by the contact area and the shear stress of the lubricant (Vakis et al., 2018). The fundamental principles of friction were first established by Guillaume Amontons (1663–1705), and are being discussed recently by Hutchings, (2021). According to Amontons' laws, the frictional force is independent of the apparent area of contact and directly proportional to the normal load applied.

Friction depends on lubrication conditions. In dry friction, direct surface contact causes high resistance, following Amontons' laws. Adding a lubricant creates boundary lubrication, where a thin film reduces metal-to-metal contact. In mixed lubrication, boundary and hydrodynamic effects act together, partially lowering friction. In hydrodynamic lubrication, a full lubricant film separates the surfaces, greatly reducing wear. Under very high loads, electrohydrodynamic lubrication (EHL) occurs, where elastic deformation and increased lubricant viscosity maintain surface separation. Understanding these lubrication regimes helps reduce friction, minimize wear, and extend component life (Chong et al., 2019; Jamalabadi et al., 2019).

2.2.2 Wear

Wear is the gradual loss or damage of material from a solid surface due to sliding, rolling, or impact. It affects the reliability, efficiency, and lifespan of components, making it important in tribology. Wear is commonly classified into five types: abrasive, adhesive, erosive, fretting, and corrosive (Blau, 1992; Totten, 2017a).

Abrasive wear occurs when hard surfaces or particles scratch a softer material, common in dusty or dirty environments (Williams, 2005). Adhesive wear happens when surfaces bond under high pressure or temperature, and material transfers as the surfaces slide (Antler, 1981; Markov, 2022). Erosive wear is caused by repeated particle impacts, seen in pipelines or turbine blades (Budinski, 2007). Fretting wear results from small, repeated movements, producing debris and fatigue cracks. Corrosive wear occurs when chemical or electrochemical reactions damage surfaces, often worsened by moisture (Celis et al., 2006).

Understanding wear is essential for designing durable components, tools like SEM were used to study wear scars and mechanisms (Sadeghi et al., 2024). Wear types often occur together; for example, machinery may experience both abrasive and adhesive wear, sometimes combined with corrosion (Allen & Ball, 1996; Zhai et al., 2021). To reduce wear, engineers select hard materials, use surface coatings, and apply lubricants. Lubricants form a protective layer, lowering friction, wear, and heat. While wear cannot be fully prevented, understanding its causes allows engineers to extend component life and improve reliability (Neville et al., 2007).

2.2.3 Lubrication

Lubrication is the process of adding a fluid between moving surfaces to reduce friction and wear. It forms a protective film that separates surfaces, prevents direct contact, dissipates heat, removes contaminants, and reduces corrosion, helping maintain system reliability (Bair et al., 2016; Sivebaek et al., 2010a). In automatic transmissions, ATF not only lubricates but also acts as a hydraulic fluid for smooth gear shifting and efficient power transfer. Lubrication occurs in three main regimes: boundary, mixed, and hydrodynamic. In boundary lubrication, the film is very thin and surface contact occurs, so additives and friction modifiers are critical. Mixed lubrication involves partial surface contact with a thin fluid film, while hydrodynamic lubrication has a full fluid film, providing optimal protection (Chong et al., 2019). The lubrication regime depends on viscosity, temperature, load, and surface roughness. In ATFs, degradation from oxidation, contamination, or additive loss weakens the film, increasing friction, wear, and heat. Treatment oils can restore performance by replenishing additives and improving film strength, maintaining transmission protection and efficiency.

2.2.3.1 Role of Lubricants

Lubricants are essential for improving efficiency and durability in automotive and industrial machinery. They form a protective film between moving surfaces, reducing friction, minimizing wear, dissipating heat, preventing corrosion, transferring power, and keeping contaminants like dust, water, or dirt away (Mobarak et al., 2014; Panchal et al., 2015). Lubricants can be liquids, greases, or solids, and its use dates to ancient times, evolving from natural oils and fats to modern mineral- and synthetic-based oils (Y. Li, Xi Gu, et al., 2019; Sharma & Singh, 2019).

The performance of a lubricant depends on equipment type, load, speed, and operating conditions. Lubrication operates in three main regimes: boundary, mixed, and hydrodynamic, often illustrated by the Strobeck curve, which shows how friction changes with viscosity, speed, and load (Y. Wang & Wang, 2013). In boundary lubrication, thin films allow direct surface contact, so anti-wear (AW) and extreme-pressure (EP) additives, like ZDDP and MoS_2, are crucial. Hydrodynamic lubrication occurs when a full fluid film separates surfaces, greatly reducing friction, while electrohydrodynamic (EHD) lubrication involves thin films under high load with elastic deformation, common in gears and rolling bearings. Mixed lubrication combines boundary and hydrodynamic effects, requiring balanced viscosity and additives.

Understanding lubricant behavior is essential for optimizing machinery performance and extending component life. Lubricants not only reduce friction and wear but also carry away heat, remove contaminants, and protect against corrosion (Bair et al., 2016; Braun et al., 2013; Jamalabadi et al., 2019; Vázquez-Quesada & Ellero, 2016). In automatic transmissions, these functions ensure smooth gear shifting, reliable power delivery, and overall durability. Advanced formulations and additives, such as nano-additives, help improve film strength and system efficiency, contributing to energy savings and sustainability.

2.2.3.2 Lubricants in the Automotive Industry

Both automobile and industrial machines can use lubricants to become more energy efficient. Some of the key roles that lubricant plays in the automobile applications are to reduce friction, transfer heat, prevent corrosion, protect against wear and transmit power that acts as a seal (Totten, 2017b; Tung & McMillan, 2004a). The technology to achieve this is well understood, but caution must be taken by both the designer of the machine and the person who formulates the lubricant to make sure that any decrease in lubricant viscosity does not lead to a reduction in durability. One of the main reasons why these lubricants aren't utilized more frequently is that frequently, lubricants are chosen only based on their price, paying little attention to how the lubricant will affect operational costs (Pirro et al., 2017).

To reduce friction and wear, lubrication adds a friction-reducing coating between the moving surfaces. Both fluid and solid materials can be degraded as lubricants. Grease and lube oil, the two most popular types of lubricants on the market, are substances that are often degraded to lubricate a surface. The application determines the kind of lubricant to use. For various applications, including those in the automotive, industrial, marine, and other fields, there are various lube oil types.

Lubricants can be classified into various types, including mineral oils, synthetic oils, bio-based oils, and greases, each tailored for specific applications (Rudnick, 2020a). Mineral oils, derived from crude oil, are widely used due to their cost-effectiveness and availability, but they may lack the high-temperature stability and oxidation resistance of synthetic options. Synthetic lubricants, including polyalphaolefins (PAO), esters, and silicones, offer superior thermal stability, lower volatility, and better oxidation resistance, making them ideal for high-performance applications. Bio-based lubricants, derived from vegetable oils and animal fats, are gaining popularity for their biodegradability and reduced environmental impact, despite challenges in oxidative stability. Greases, composed of a base oil, thickener, and additives, are preferred in applications requiring adhesion to surfaces and protection against contaminants, such as bearings and chassis components (Afonso et al., 2023; Rudnick, 2020a).

Automotive lubricants are essential for various systems, including engines, transmissions, differentials, and braking mechanisms. Engine oils, the most widely used automotive lubricants, are formulated with base oils and performance-enhancing additives to withstand extreme temperatures, high pressures, and oxidation. Other essential lubricants include transmission fluids, gear oils, greases, and hydraulic fluids, each designed to meet the specific demands of automotive components. The proper selection of lubricants is crucial for reducing maintenance costs, improving fuel efficiency, and enhancing overall vehicle performance. The types of lubricants used in automobiles are shown in Table 2.1.

Table 2.1
Types of Lubricants

Type of Lubricants	Description
Automotive Transmission Fluid	A type of transmission fluid degraded in cars with automatic transmissions is called ATF.
Engine Oil	It comprises base oils that have been upgraded with a variety of additives, including viscosity index improvers for multi-grade oils, detergents, and anti-wear additives. Internal combustion engines are lubricated using motor oil.
Gear Oil	To deal with the sliding action of hypoid bevel gears and combat wear, gear oil typically has a high viscosity and contains extreme pressure (EP) additives made of phosphorus-sulphur compounds.
Greases	To avoid any accelerated wear and tear, grease is utilised in the steering and suspension joints. Oil and thickeners are degraded to make it. The lubricating oil may be synthetic or made of petroleum, and its viscosity may vary.
Brake Fluids	All automotive applications employ brake fluids to maintain and enhance the functionality of the braking systems.
Hydraulic Oil	To fight wear and corrosion, hydraulic oils are typically produced from base oils plus a package of additives.

The efficacy of a lubricant depends not only on its base oil but also on the additives incorporated to enhance performance. Additives such as anti-wear agents, extreme pressure (EP) additives, antioxidants, detergents, dispersants, and viscosity index (VI) improvers play crucial roles in extending equipment life, maintaining cleanliness, and ensuring consistent performance under varying conditions. Understanding the interaction between base oils and additives is essential for developing tailored lubrication solutions that meet the unique demands of different machinery and operating environments.

2.3 Automatic Transmission Fluid (ATF)

ATF are among the most complex and specialized lubricants, designed to meet the rigorous demands of modern automatic transmission systems. Unlike conventional lubricants that primarily focus on minimizing friction and wear, ATFs must achieve a delicate balance: reducing friction to prevent wear while simultaneously enabling controlled friction for the effective engagement of clutch materials. This dual requirement underscores the high degree of specialization in ATF formulations, which are often tailored to Original Equipment Manufacturer (OEM) specifications or even specific transmission models, given the proprietary frictional materials employed by OEMs.

Beyond friction management, ATFs are engineered to perform reliably under a wide range of operating conditions. They must maintain stable performance across extreme temperatures, resist degradation over extended service intervals, and ensure compatibility with diverse transmission components such as seals, gaskets, and metal surfaces. These multifaceted requirements demand a sophisticated blend of chemical and physical properties, reflecting the complexity of ATF formulations and their compliance with stringent industry standards.

2.3.1 Functions of ATF

ATF plays a crucial role in ensuring the smooth operation and longevity of an automatic transmission system. One of its primary functions is lubrication, where it reduces friction between moving components such as gears, bearings, and clutch plates. This lubrication minimizes wear and tear, preventing premature failure of transmission parts and ensuring efficient power transfer within the system (Kemp & Linden, 1990).

Another key function of ATF is cooling. The transmission generates significant heat due to friction and hydraulic pressure during operation. ATF absorbs and dissipates this heat, preventing excessive temperatures that could lead to fluid degradation, seal damage, and reduced transmission efficiency. The cooling properties of ATF help maintain optimal operating conditions, extending the lifespan of both the fluid and the transmission components.

ATF also acts as a hydraulic medium, enabling smooth gear shifts in an automatic transmission (Latip et al., 2016). It transmits power and pressure to engage and disengage clutch packs and bands, allowing for seamless gear changes. The fluid's ability to maintain stable viscosity and flow properties is essential for precise hydraulic control, ensuring smooth acceleration and optimal fuel efficiency.

Additionally, ATF provides cleaning and protection by suspending contaminants and preventing the buildup of sludge, varnish, and deposits within the transmission (Latip et al., 2016). Many ATFs contain detergents and dispersants that help keep internal components clean, reducing the risk of clogging in narrow passages and prolonging overall transmission performance.

ATF helps in sealing and corrosion prevention. It forms a thin film on metal surfaces, reducing oxidation and preventing rust formation. It also enhances the sealing properties of gaskets and O-rings, maintaining proper fluid pressure and preventing leaks. By performing these critical functions, ATF ensures that the transmission operates efficiently, smoothly, and reliably over an extended period.

2.3.2 Properties of ATF

ATF plays a critical role in the performance and longevity of automatic transmissions. It provides lubrication, cooling, and hydraulic pressure within the system. Key properties include a high viscosity index for stable lubrication across temperatures (Martini et al., 2018a; Okrent, 1961), anti-foaming agents to prevent bubbles (Barr et al., 2019), and thermal stability to withstand heat during operation (Mujtaba et al., 2021). ATF is formulated to resist oxidation, prevent sludge and deposits, and maintain low-temperature fluidity for smooth operation in cold conditions. Its chemical composition also ensures proper friction characteristics for smooth gear shifts. ATF properties are carefully balanced to ensure reliable, efficient, and durable transmission performance under diverse driving conditions. The following table summarizes the technical specifications of various fresh ATF samples, highlighting critical parameters such as viscosity, viscosity index (VI), pour point, and flash point. These properties are essential for evaluating ATF performance under diverse operating conditions. Table 2.2 shows the technical specification of fresh ATF samples.

Table 2.2
Technical Specifications of Fresh ATF Samples from Suppliers

Characterization			**Reference ATF**		
	ATF A_0	**ATF B_0**	**ATF C_0**	**ATF D_0**	**ATF E_0**
Colour	Red	Red	Red	Red	Red
Kinematic Viscosity at 40°C (cSt)	~30-40	~34-37	~50-60	~70-80	33.39
Kinematic Viscosity at 100°C (cSt)	~6-7.5	~7-8	~8-9	~11-13	7.39
Viscosity Index (VI)	~180	~170	~128	~156	168
Pour Point	-45°C	-45°C	NIL	NIL	-45°C
Flash Point	>180°C	>180°C	NIL	NIL	195°C
Density at 15°C (g/cm^3)	~0.860	~0.855	NIL	NIL	~0.865

ATFs play a crucial role in ensuring the longevity, efficiency, and reliability of automatic transmission systems. Parameters such as viscosity and flash point directly influence the fluid's ability to perform effectively under varying operating conditions. Consequently, a comprehensive understanding of ATF properties is vital for selecting the appropriate fluid for specific applications, contributing to optimal transmission performance.

2.3.3 Composition of ATFs

ATF is a specialized lubricant formulated to meet the demanding requirements of automatic transmissions. Its performance depends on a carefully designed combination of base oils and additives, each serving a specific function to ensure efficiency, durability, and compatibility with system components. Base oils, which make up 70–90% of ATF, act as carriers for additives and can be mineral-based, synthetic, or blends. Synthetic oils, such as polyalphaolefins (PAOs) or esters, are preferred for their superior thermal stability, oxidation resistance, and low-temperature fluidity. Additives enhance ATF performance in various ways: viscosity modifiers maintain consistent fluidity across temperatures, friction modifiers control clutch engagement and minimize slippage, and anti-wear or extreme pressure agents protect metal surfaces from damage. Detergents and dispersants remove deposits and suspend contaminants, antioxidants prevent sludge and varnish formation, foam inhibitors reduce air bubbles, and seal conditioners preserve rubber elasticity. Colorants, typically red, aid in leak detection and fluid identification. Together, these components ensure ATF provides effective lubrication, reduces wear, maintains system cleanliness, and supports smooth transmission operation, ultimately improving the reliability and lifespan of the transmission system.

2.3.3.1 Base Oils

The evolution of automatic transmission systems has significantly influenced the performance requirements for ATFs. Modern designs emphasize driving comfort, fuel efficiency, and longevity, making it essential for ATFs to meet stringent standards. In response to these demands, advanced base oils, specifically API Group III and IV oils, have become critical components in ATF formulations (Moon & Yang, 2001). These base oils offer unique properties that directly enhance the performance and durability of ATFs.

Group III base oils, commonly referred to as hydrocracked base oils, are produced from highly refined mineral oils through severe hydrocracking, hydroisomerization, and hydrotreating processes. These processes significantly reduce impurities such as sulfur, nitrogen, and aromatic compounds, resulting in a highly purified base oil with improved molecular uniformity. Consequently, Group III base oils exhibit high oxidative stability, low volatility, and a high viscosity index, enabling them to maintain stable viscosity and resist thermal degradation under high-temperature operating conditions. Due to these enhanced properties, Group III base oils provide performance characteristics that approach those of synthetic base oils. In contrast, Group IV base oils, composed of polyalphaolefins (PAOs), are fully synthetic and chemically engineered to deliver excellent low-temperature fluidity, thermal stability, and oxidation resistance. These characteristics make both Group III and Group IV base oils suitable for the demanding operating conditions of modern automatic transmissions.

One of the primary advantages of using Group III and IV base oils in ATFs is their ability to maintain stable frictional properties over time. The frictional characteristics of ATFs are crucial for the smooth operation of clutches and bands, enabling efficient power transfer and reducing wear. Research has demonstrated that these advanced base oils retain superior frictional performance even as the fluid degrades, ensuring smooth gear shifts, reduced energy losses, and enhanced fuel efficiency (Prasannakumar et al., 2025).

Low-temperature fluidity is another critical aspect of ATF performance, particularly in colder climates. Group III and IV base oils excel in maintaining their viscosity at sub-zero temperatures, ensuring reliable operation during cold starts and minimizing wear in such conditions. This property is essential for consistent transmission response and the prevention of sluggish operation in extreme cold.

In addition to their frictional and low-temperature benefits, Group III and IV base oils offer superior oxidation stability. By resisting the formation of sludge, varnish, and acids caused by oxidation, these oils help maintain the integrity of ATFs over extended service intervals. This reduces the frequency of oil changes and contributes to the overall efficiency and cost-effectiveness of automatic transmissions. Furthermore, their compatibility with seals and gaskets prevents issues such as leakage or seal hardening, ensuring better long-term reliability.

The use of API Group III and IV base oils in ATF formulations significantly improves performance in areas such as friction stability, low-temperature fluidity, oxidation resistance, and seal compatibility. These benefits align with the evolving requirements of modern automatic transmissions, making advanced base oils indispensable for achieving optimal efficiency, reliability, and longevity.

2.3.3.2 Viscosity Grades for ATF

Viscosity is one of the most critical factors influencing the performance of ATF. It governs the fluid’s ability to flow, lubricate, and maintain hydraulic pressure under a wide range of operating temperatures. The viscosity grade of ATF plays a pivotal role in ensuring smooth transmission operation, optimal energy transfer, and the protection of internal components from wear and damage. ATFs are designed with specific viscosity grades to meet the diverse demands of various transmission systems. These grades are carefully formulated to maintain fluidity at low temperatures for cold starts while retaining adequate thickness to protect components at high operating temperatures (Newcomb et al., 2007a). The challenge lies in achieving a balance between these extremes, which is critical for modern automatic transmissions that operate under increasingly complex and demanding conditions.

Research into the viscosity grades of ATF focuses on understanding their impact on transmission performance, fuel efficiency, and system longevity. It also delves into the formulation of multi-grade ATFs using advanced base oils and viscosity index (VI) improvers, which help the fluid adapt to changing temperatures without significant loss in performance (Vickerman et al., 2010). Additionally, studies on viscosity grades often investigate their compatibility with different transmission designs, such as continuously variable transmissions (CVTs), dual-clutch transmissions (DCTs), and traditional torque converter systems. These investigations are vital for developing ATFs that meet the specific requirements set by original equipment manufacturers (OEMs) and for advancing the design of future transmission technologies. The research on viscosity grades of ATF not only enhances the understanding of fluid dynamics within transmission systems but also aids in optimizing fuel economy, reducing emissions, and improving the overall reliability of modern vehicles.

2.3.4 Additives in ATF

ATFs are formulated with a variety of additives to improve their performance and longevity in the demanding environment of automatic transmissions. Anti-wear agents, such as zinc dialkyldithiophosphate (ZDDP), are crucial in forming protective layers on metal surfaces, minimizing friction and wear between components like gears and clutch materials. Detergents help maintain the cleanliness of the fluid by neutralizing acidic by-products formed during oxidation and thermal degradation. This prevents the formation of harmful deposits on metal surfaces within the transmission system. Dispersants function to keep contaminants such as soot, oxidation products, and wear particles suspended in the fluid. By preventing these particles from agglomerating, dispersants help avoid the formation of sludge that could impair transmission performance. Viscosity index improvers are vital for ensuring consistent fluid viscosity over a wide temperature range, especially given the extreme operating conditions in transmissions. Antioxidants prevent oxidation, which can degrade the fluid over time, ensuring a longer lifespan for the ATF. Friction modifiers are used to control the frictional properties of the fluid, which is essential for smooth shifting and fuel efficiency. Corrosion inhibitors in ATF formulations protect internal components from rust, while pour point depressants enhance low-temperature performance, ensuring fluid flow even in cold conditions. Anti-foaming agents are also included to prevent the formation of bubbles, which can hinder lubrication efficiency, while extreme pressure (EP) additives protect the transmission under heavy load conditions, ensuring reliable operation. The careful selection and concentration of these additives are tailored to meet the specific demands of different transmission systems, contributing to the overall effectiveness, durability, and performance of ATFs under a variety of operating conditions.

2.3.4.1 Types and Functions of Additives

Additives play a pivotal role in the formulation of ATFs, enhancing their performance, durability, and adaptability to the demanding operational conditions of automatic transmissions. These additives work synergistically to address a wide range of challenges, ensuring that ATFs can meet the specific requirements of ATF. Table 2.3 shows the type of additive and its function.

Table 2.3
The Types Of Additives And Its Function (Boussaid et al., 2024; Costello, 2017; Fry et al., 2020; Kamis et al., 2024; Seddon et al., 2010; Xia et al., 2024).

Type of Additives	Function
Dispersants	Sludge & varnish control
Antioxidants	Prohibit oxidation
Anti-wear	Planetary gear, bushing, thrust washer protection
Friction modifier	Modify clutch plate and band friction
Corrosion inhibitor	Prevent corrosion and rust
Seal swell agent	Prevent loss of fluid via seals
Viscosity Improver	Reduce rate of change of viscosity
Pour Point Depressant	Improve low temperature fluidity
Foam inhibitor	Foam control
Red dye	Identification

One of the most critical additives is anti-wear agents, such as zinc dialkyldithiophosphate (ZDDP). These compounds form a robust protective film on metal surfaces, reducing friction and wear between high-contact components like planetary gears, bushings, and thrust washers (Fatima, Minami, et al., 2015). This protection ensures the longevity of transmission components, even under high-stress conditions.

Maintaining fluid cleanliness is crucial for preventing performance degradation, and dispersants and detergents play a central role in achieving this (Kumar & Tyagi, 2014). Dispersants suspend contaminants in the fluid, preventing sludge and varnish buildup, while detergents neutralize acids formed during operation. Together, they ensure that the transmission system remains clean, efficient, and free from harmful deposits.

Viscosity improvers are vital for maintaining consistent viscosity across a wide range of operating temperatures. These additives prevent the fluid from thinning excessively in high temperatures or becoming too thick in cold conditions, ensuring effective lubrication and hydraulic performance (Canter, 2011; Stambaugh & Kinker, 2010). This adaptability is critical for transmissions subjected to variable climate and operational demands.

Antioxidants are included to inhibit oxidative degradation of the fluid, which can lead to the formation of acids, sludge, and varnish. By extending the oxidative stability of ATFs, these additives enhance fluid lifespan and ensure consistent performance over time, reducing the need for frequent replacements.

Friction modifiers are essential for ensuring smooth clutch engagement and gear shifts, contributing to driving comfort and fuel efficiency. By carefully managing the frictional properties of the fluid, these additives also reduce wear on clutch plates and bands, extending their service life.

To prevent rust and corrosion, especially in environments with high humidity or water exposure, corrosion inhibitors are added to the formulation. These additives create a protective barrier on metal surfaces, safeguarding critical components from rust and degradation. Additionally, seal swell agents maintain the integrity of seals by preventing shrinkage and leaks, thus avoiding fluid loss and maintaining system efficiency.

ATFs must perform effectively across a wide temperature range. Pour point depressants ensure low-temperature fluidity, enabling the fluid to flow even in sub-zero conditions. Anti-foaming agents prevent the formation of bubbles during operation, which can compromise lubrication and hydraulic efficiency. In high-stress scenarios, extreme pressure (EP) additives provide added protection by forming a durable film that minimizes wear and tear under heavy loads.

Additional additives like demulsifiers may be used to separate water from the fluid, preventing contamination and maintaining the lubricant's effectiveness. Some formulations also include anti-shudder agents to minimize vibration and shudder during gear shifts, further enhancing driving comfort.

The red dye is included in ATFs for easy identification. This visual distinction simplifies maintenance by helping technicians quickly differentiate ATF from other vehicle fluids, ensuring the correct fluid is used during servicing.

The diverse array of additives in ATFs is tailored to address the unique demands of automatic transmissions. Each additive plays a specific role, from wear protection and cleanliness to temperature adaptability and operational stability. This sophisticated formulation ensures that ATFs can meet the rigorous performance, durability, and efficiency requirements of modern transmission systems.

2.3.4.2 Elemental Composition and Functional Roles

Certain elemental components play a critical role in the performance and effectiveness of ATFs. These elements, incorporated as part of additive formulations, contribute to the fluid's ability to meet the demanding requirements of modern transmission systems. Table 2.4 summarizes the key elements used as additives in ATFs and their respective roles.

Table 2.4
Roles of elements as additives

Element	Findings	Reference
Phosphorus (P)	The phosphorus–graphene hybrids (P–Gr) with different P/Gr mass ratios attributed the excellent **friction reducing** and AW performances of P–Gr hybrid in PAG base oil.	(Wu et al., 2018)
	The addition of BP nanosheets modified by NaOH (BP-OH) to water can result in **robust super lubricity** when the additive concentration, contact pressure, and sliding velocity are substantially changed.	(Wu et al., 2018)
	The Ag/BP nanomaterials during scratching serve not only as a **friction-reducing** and **anti-wear additive** but also as a catalyst to decompose the base PAO oil for forming a carbon-based tribo-films under ambient conditions that further reduces the friction and wear.	(G. Tang et al., 2020)
Molybdenum (Mo)	The role of sulphur-containing molybdenum compound additives as inhibitors of oxidation of hydrocarbon materials thus acts as **friction modifiers**.	(Parenago et al., 2017b)
	It is found that the closed structure and chemical inertness-like qualities of the MoS2 nanoball make it an excellent **lubricant** when added to polyoxymethylene. MoS2 based nanofluids enhance the heat transfer coefficient due to motion and nanoparticle migration. This increase in thermal conductivity and heat transfer coefficient, thus, increases the heat dissipation capacity of nanofluids	(Singh et al., 2020)
Barium (Ba)	It was found that barium and over base barium sulfonates were very effective as **rust preventatives** (RPs) in slushing oils, and this became the de facto standard.	(Costello, 2017)
Calcium (Ca)	Tribological test results have shown that there is an improvement in the **anti-wear**, **extreme-pressure (EP)** properties in the study of tribological properties of castor oil with calcium–copper–titanate nanoparticles (CCTO) and zinc dialkyldithiophosphate (ZDDP) additives.	(R. N. Gupta & Harsha, 2016)
Magnesium (Mg)	It shows that the modified magnesium silicate hydroxide (MSH) containing oil exhibits better **anti-wear** properties than the base oil, with the highest rate of wear reduction reaching 55%. In addition, different test conditions, such as load and rotation speed, have an influence on the anti-wear properties of MSH.	(Gao et al., 2018)

	The tribological test results show that the **anti-friction** performance and **wear resistance** of the friction pair were improved by using magnesium silicate hydroxide (MSH).	(Gao et al., 2018)
Boron (B)	It was observed that adding boron-doped lubricating oil in a gasoline engine provides a relative **improvement in engine performance** and emissions.	(Akbiyik et al., 2022)
	The analysis of the worn scar surface demonstrates that CPBA-BNNSs can form a protective tribo-film containing boron and nitrogen elements on the rubbing surfaces, thereby **decreasing the friction** and **protecting the surfaces** from wear.	(W. Wang et al., 2018a)
Zinc (Zn)	ZnO particles are found to be conducive to **reducing the friction and wear.**	(Singh et al., 2020)
	The research of the tribological properties of castor oil with calcium-copper-titanate nanoparticles (CCTO) and zinc dialkyldithiophosphate (ZDDP) additions has showed improvement in the **anti-wear**, **extreme-pressure (EP)** capabilities.	(R. N. Gupta & Harsha, 2016)
Copper (Cu)	Nano-copper and copper oxide additives help improve the tribological properties, like **reducing the friction coefficient and wear** and **increasing the anti-wear** properties.	(Singh et al., 2020)
Silicon (Si)	The **viscosity of lubricant increased** with the increasing concentration of silica nanoparticles.	(Sui et al., 2018)
	It was experimentally proven that silica nanoparticles can greatly reduce both **wear and friction**.	(Ding et al., 2018)
Sulphur (S)	The role of sulphur-containing molybdenum compound additives as inhibitors of oxidation of hydrocarbon materials thus acts as **friction modifiers**.	(Parenago et al., 2017b)

2.3.5 Degradation of ATF and Performance Loss

ATF degrades over time due to prolonged exposure to heat, mechanical stress, and contamination. As ATF deteriorates, it loses its ability to effectively lubricate, cool, and facilitate smooth gear shifts, leading to increased friction, wear, and potential transmission failures. The degradation process is influenced by oxidation, shearing forces, and the depletion of essential additives, all of which negatively impact the fluid’s performance.

One of the primary causes of ATF degradation is oxidation and thermal breakdown (Maeda & Murakami, 2003). ATF operates under high temperatures, and continuous exposure to heat accelerates oxidation, causing the formation of sludge and varnish deposits. These deposits can clog transmission passages, leading to inefficient lubrication and reduced hydraulic performance. Additionally, mechanical shearing from constant movement through gears and clutch plates can break down the ATF's viscosity modifiers, causing a loss of viscosity stability and reducing its ability to maintain a protective film between moving components (Halley et al., 2020a).

Contamination also plays a significant role in ATF degradation. Over time, metal wear particles, dirt, and moisture can enter the fluid, leading to increased abrasive wear and corrosion of transmission components (Fatima et al., 2014; Fatima, Holmgren, et al., 2015). The depletion of vital additives, such as anti-wear agents and detergents, further reduces ATF effectiveness, resulting in rough shifting, transmission overheating, and gear slippage. These issues not only compromise driving comfort but also increase maintenance costs due to premature ATF replacement or transmission repairs.

To address these challenges, treatment oils have been developed to restore and enhance the performance of used ATF. These treatments claim to replenish depleted additives, improve viscosity, and enhance anti-wear properties. However, the effectiveness of such treatments in prolonging ATF life and maintaining transmission efficiency remains uncertain. This study aims to evaluate whether treatment oils can effectively restore key fluid properties and improve the overall reliability of used ATF in automatic transmissions.

2.4 Treatment Oil for ATF

Treatment oil for ATF is designed to enhance the performance of used or degraded ATF by replenishing essential additives, improving lubrication, and restoring viscosity. Over time, ATF loses its effectiveness due to oxidation, shearing, and contamination, leading to issues such as rough shifting, increased friction, and accelerated wear on transmission components (Newcomb et al., 2007b; Tung & McMillan, 2004b). Treatment oils aim to mitigate these problems by introducing friction modifiers, anti-wear agents, and viscosity stabilizers to restore ATF properties.

One of the primary functions of treatment oil is to enhance lubrication and reduce friction between transmission components. By replenishing depleted anti-wear additives, treatment oil helps maintain a protective film between metal surfaces, reducing gear wear and preventing overheating (Pawlak, 2003). Some formulations also contain seal conditioners, which help prevent leaks by softening and expanding aging transmission seals, ensuring better fluid retention and pressure regulation.

In addition to lubrication, treatment oils contain detergents and dispersants that assist in cleaning transmission components by dissolving sludge and varnish deposits formed during ATF degradation (Seddon et al., 2010). This can help improve fluid circulation and prevent clogging in transmission passages, contributing to smoother gear shifts and more efficient power transfer. Some treatment oils also claim to enhance the oxidation stability of ATF, slowing down further degradation and extending fluid life.

Despite these potential benefits, the effectiveness of treatment oils in restoring ATF performance remains a topic of debate. Factors such as compatibility with different ATF formulations, long-term stability, and potential side effects on frictional behaviour need to be carefully evaluated. Some treatment oils may alter the coefficient of friction in a way that affects shift quality, while others might not provide lasting improvements. This study aims to assess the impact of treatment oil on used ATF by analysing changes in physicochemical and tribological properties, determining whether these additives truly enhance fluid performance and extend transmission life.

2.4.1 Purpose and Composition of Treatment Oils

Treatment oils are specialized lubricant enhancers formulated to restore or improve the performance of used lubricants such as ATFs. Their primary purpose is to replenish depleted additives, reduce friction, minimize wear, and enhance the overall stability of aged fluids (Chong et al., 2019). Typically, treatment oils contain a blend of detergent, dispersant, anti-wear, antioxidant, friction modifier, and extreme pressure (EP) additives. These components work together to clean internal surfaces, neutralize harmful by-products of oxidation, and reinforce the lubricant's protective film. When added in small concentrations, treatment oils help extend lubricant service life and maintain reliable operation of transmission systems without requiring a complete fluid replacement.

2.4.2 Mechanism of Action in Restoring Used ATF

The restoration mechanism of treatment oils in used ATF involves both chemical replenishment and physical stabilization of degraded components. Over time, ATF loses its functional additives and undergoes oxidation, leading to increased friction, sludge formation, and reduced viscosity stability. When treatment oil is added, its active components such as antioxidants, detergents, dispersants, and anti-wear agents rejuvenate the fluid by neutralizing acidic by-products, dispersing contaminants, and reinforcing the protective film on metal surfaces. Friction modifiers and viscosity improvers further help restore smooth torque transmission and maintain film thickness under varying temperatures.

With continued use, vital additives like anti-wear compounds and antioxidants are depleted, reducing the fluid's protective efficiency. Treatment oils directly replenish these additives, restoring critical lubricating and anti-wear functions (Sivebaek et al., 2010b). As oxidation progresses, acids and sludge precursors form; detergent and dispersant additives in treatment oils help neutralize and remove these by-products, improving fluid cleanliness and stability (Sivebaek et al., 2010b). Additionally, friction modifiers and extreme pressure (EP) agents re-establish the dynamic lubricating film, minimizing direct metal contact that causes wear and localized overheating (Fowell et al., 2014). By restoring proper frictional characteristics, treatment oils enable smoother clutch engagement and more consistent gear shifts (Bair et al., 2016).

2.4.3 Performance Improvement Reported in Previous Studies

Previous studies have demonstrated that the incorporation of additives or treatment oils can improve the tribological performance ATF, particularly in terms of friction stability, wear protection, and lubrication performance. The performance of ATF is strongly influenced by the interaction between base oil, additive packages, and friction materials within the transmission system. Research on ATF friction behaviour has shown that the formulation of additives plays a crucial role in maintaining appropriate friction characteristics required for smooth clutch engagement and transmission durability (Tipton & Schiferl, 1997).

Friction modifiers are among the most important additives used in ATF formulations. These compounds function by forming surface-active layers on metal and friction material interfaces, thereby reducing direct surface contact and stabilizing the coefficient of friction during sliding conditions. Experimental investigations using scanning force microscopy have shown that the addition of friction modifiers can significantly reduce dynamic friction, particularly under low sliding speeds where boundary lubrication dominates. This improvement contributes to more stable friction characteristics and helps prevent vibration phenomena such as clutch shudder in automatic transmissions (Slough, 1979).

Further studies have also examined the influence of specific friction modifiers on the tribological behaviour of ATF. For instance, the addition of glycerol monoisostearate has been reported to promote tribo-chemical reactions between detergent and anti-wear additives, resulting in the formation of calcium hydroxyphosphate tribo-films on the contact surfaces. These tribo-films provide protective surface coverage that improves lubrication stability and enhances friction performance during clutch operation (Zechao et al., 2023).

Tribological investigations of commercial ATFs have also shown that the formation of surface tribo-films plays a critical role in controlling friction behaviour. Disc-on-disc tribometer studies revealed that the chemical composition and stability of these tribo-films significantly influence friction characteristics and anti-shudder performance in wet clutch systems (Di et al., 2020a).

Previous research indicates that the incorporation of additives or treatment oils can enhance the friction and wear characteristics of ATF through mechanisms such as additive replenishment, surface film formation, and improved boundary lubrication. These improvements contribute to better transmission performance, smoother clutch engagement, and increased durability of transmission components.

2.4.4 Compatibility with Existing ATF Formulations

Compatibility between treatment oils and existing ATF formulations is an important factor that determines the effectiveness and safety of additive supplementation. ATF formulations are carefully balanced mixtures consisting of base oils and complex additive packages such as friction modifiers, anti-wear agents, detergents, dispersants, antioxidants, and viscosity modifiers. These additives are designed to function synergistically to maintain stable friction characteristics, wear protection, and thermal stability under varying operating conditions. Any external additive or treatment oil introduced into the system may alter this balance and potentially affect the performance of the original formulation.

Previous research has highlighted that additive compatibility is essential to ensure that newly introduced additives do not interfere with existing chemical interactions within the lubricant system. Incompatible additives may lead to additive depletion, precipitation, or reduced effectiveness of existing components. For example, excessive concentrations of friction modifiers can alter the friction–speed characteristics required for proper clutch engagement in automatic transmissions. Such changes may lead to undesirable effects such as clutch slippage, shudder, or inconsistent friction behaviour during operation.

The interaction between treatment oils and base oils must also be considered. Modern ATF formulations are typically developed using specific base oil groups and additive chemistries optimized for transmission systems. Introducing treatment oils with different chemical compositions may influence viscosity behaviour, oxidation stability, and lubrication performance. Studies on lubricant additive interactions have shown that certain additive combinations can either enhance or suppress tribo-film formation, which directly affects friction and wear characteristics at the sliding interface.

Compatibility with transmission components such as seals, friction materials, and metal surfaces is another critical aspect. Some additive compounds may cause swelling or degradation of elastomer seals or alter the surface chemistry of friction materials used in wet clutch systems. These interactions may lead to long-term reliability issues if the treatment oil is not formulated to match the chemical characteristics of the original ATF.

The compatibility of treatment oils with existing ATF formulations remains a key consideration when evaluating their effectiveness in restoring or improving used transmission fluids. While treatment oils may provide certain performance benefits through additive replenishment, their interactions with the original lubricant formulation must be carefully evaluated to avoid negative effects on friction behaviour, component durability, and overall transmission performance.

2.4.5 Current Challenges

Despite the potential benefits of treatment oil in restoring and enhancing used ATF, several challenges exist regarding its effectiveness, compatibility, and long-term impact. One of the primary concerns is the variability in ATF formulations, as different manufacturers use unique additive packages tailored to specific transmission systems (Newcomb et al., 2007c; Tung & McMillan, 2004c). Treatment oils may not always be compatible with these formulations, potentially altering the fluid's performance in unintended ways. For instance, changes in the coefficient of friction could lead to inconsistent gear shifts, increased wear, or even transmission damage in some cases.

Another challenge is the uncertainty of long-term effectiveness. While treatment oils may provide short-term improvements in lubrication and viscosity, their ability to sustain these benefits over extended periods is not well-documented. Additive depletion, oxidation stability, and the overall durability of the treated ATF under real-world driving conditions remain areas of concern (Caines et al., 2004). Some treatment oils might only mask existing problems temporarily rather than truly restoring the ATF's lost properties, leading to premature transmission failures if the underlying issues are not properly addressed.

Additionally, the lack of standardized testing and transparency in treatment oil formulations poses a challenge in evaluating their reliability. Many commercial treatment oils do not disclose their exact composition, making it difficult to determine their interaction with existing ATF additives. Without proper testing based on industry standards, such as ASTM or OEM specifications, there is a risk of unintended chemical reactions that could accelerate fluid degradation rather than improve it.

The cost-effectiveness of treatment oils compared to ATF replacement is a key factor to consider. While treatment oils offer a more affordable alternative to full ATF replacement, their actual impact on extending ATF lifespan and reducing maintenance costs is still uncertain. If a treatment oil does not effectively restore fluid performance, vehicle owners may still need to replace the ATF prematurely, leading to additional expenses.

2.4.6 Research Gap

Numerous studies have investigated the tribological behaviour and formulation of ATFs, limited attention has been given to the effectiveness of treatment oils in restoring the performance of degraded or used ATFs. Most previous research has focused on the development of new ATF formulations and the role of additive packages in improving friction stability, wear protection, and oxidation resistance in fresh lubricants (Cameron et al., 2004; Di et al., 2023; Moon Woo-Sik, 2022; Moon & Yang, 2001). There is comparatively less experimental evidence addressing how treatment oils influence the tribological behaviour of used ATF after prolonged service conditions.

Existing studies have generally evaluated lubricant performance using standardized clutch tests or conventional tribological methods that simulate transmission operation. However, many of these studies emphasize fresh lubricant formulations rather than the restoration of degraded fluids (Di et al., 2023; Fatima et al., 2014). The behaviour of used ATF is significantly different due to additive depletion, contamination, and chemical degradation that occur during operation. While treatment oils are commonly marketed as a solution to restore lubrication performance, there is limited published data that systematically examines their effectiveness under controlled tribological testing conditions.

The interaction between treatment oil additives and the remaining additive system in used ATF has not been extensively investigated. The complexity of additive interactions makes it difficult to predict whether the addition of treatment oil will fully restore the friction characteristics required for proper transmission operation. There is insufficient research evaluating how treatment oils influence the coefficient of friction and friction stability when mixed with degraded ATF.

Further investigation is necessary to evaluate the tribological performance of used ATF after the introduction of treatment oil under controlled experimental conditions. Studies focusing on friction behaviour using reciprocating sliding tests remain limited. Addressing this gap will provide a clearer understanding of how treatment oils influence the friction characteristics of used ATF and whether they can effectively restore lubrication performance. This study aims to contribute to this area by evaluating the coefficient of friction behaviour of treated used ATF using a reciprocating tribological test method.

2.5 Characteristics of ATF

The effectiveness of ATFs relies heavily on their properties, which directly influence the performance, durability, and reliability of automatic transmission systems. Key characteristics such as viscosity, thermal stability, oxidation resistance, and frictional behaviour determine how well an ATF can withstand the demands of modern transmission designs (Halley et al., 2020; Newcomb et al., 2007b). Measuring these properties is critical not only for ensuring compliance with industry standards but also for optimizing performance under various operating conditions.

This section explores the fundamental properties of ATFs, the methodologies used to evaluate their performance, and the importance of these assessments in maintaining transmission efficiency and longevity. From viscosity measurements to friction tests, each parameter provides valuable insights into how ATFs contribute to seamless vehicle operation and system protection.

2.5.1 Fundamental Physicochemical Properties of Substance in ATF

The performance and longevity of an automatic transmission system are heavily dependent on the physiochemical properties of the ATF, which determine its functionality under varying operating conditions. The physiochemical properties of ATF encompass a broad range of characteristics, including viscosity, thermal stability, oxidation resistance, and chemical compatibility with transmission components. Viscosity is one of the most critical properties, as it affects the fluid's ability to flow under different temperature conditions, ensuring adequate lubrication and hydraulic efficiency (Ba Geri et al., 2019; Martini et al., 2018b). Thermal stability and oxidation resistance are equally vital, as they determine the fluid's durability and its ability to maintain performance despite exposure to high temperatures and prolonged use. Other key physiochemical properties include frictional characteristics, which influence the smoothness of gear shifts and the prevention of slippage, and corrosion inhibition, which protects internal transmission components from wear and damage. Additionally, ATF must exhibit resistance to foam formation and maintain its properties over time without significant degradation.

Modern ATFs are formulated with a combination of highly refined base oils and advanced additive packages to optimize these properties, meeting the rigorous demands of various transmission designs (Rudnick, 2020b). Understanding these physiochemical properties is essential for the development, selection, and evaluation of ATF, ensuring compatibility with specific transmission systems and adherence to manufacturer specifications. This test determines the kinematic viscosity of liquid oil by measuring the time it takes for the liquid to flow through a calibrated glass capillary viscometer. The dynamic viscosity is then calculated by multiplying the kinematic viscosity by the liquid's density. This method is best suited for liquids where shear stress and shear rates are proportional, and it covers a wide viscosity range (0.2 mm^2/s to 300,000 mm^2/s) (S. V Gupta, 2014; Viswanath et al., 2007). This test technique outlines a process for calculating the kinematic viscosity, or v, of transparent and opaque liquid oil products by timing how long it takes for a volume of the liquid to flow through a calibrated glass capillary viscometer. By dividing the kinematic viscosity by the liquid's density, one can get the dynamic viscosity.

The outcome of this test method depends on how the sample behaves and is recommended for use with liquids for which the shear stress and shear rates are primarily proportional. However, if the viscosity greatly fluctuates with the rate of shear, viscometers with various capillary sizes may produce varying values. This test method covers a range of kinematic viscosities from 0.2 mm^2/s to 300 000 mm^2/s at all temperatures. For this research, the temperature range would be 40˚C to 100˚C with an increment of 10. Thus, a graph of temperature and kinematic viscosity can be plotted. The temperature range was chosen by considering the temperatures that may be attained in the transmission (by the gears) and in the major components of the EM (if the latter was included in the transmission housing). From the plotted graph, the relation between temperature and kinematic viscosity can be determined.

2.5.1.1 Elemental Analysis

Elemental analysis of ATF is a crucial diagnostic tool for assessing fluid condition, detecting contamination, and identifying wear-related issues. This process helps determine the presence and concentration of key metals such as iron (Fe), copper (Cu), and aluminum (Al), which are commonly associated with wear from transmission components like gears, bearings, and seals. Additionally, elemental analysis can identify contaminants such as dirt, water, and fuel, which accelerate ATF degradation and impact transmission performance.

To conduct elemental analysis, advanced spectrometric techniques are commonly used. These include Spectroil Q100, Inductively Coupled Plasma (ICP) spectroscopy, X-ray Fluorescence (XRF), and Optical Emission Spectrometry (OES) (Kumbár et al., 2014; Ojeda et al., 1993; Pehlivan et al., 2008). These techniques offer high sensitivity and precision, allowing for early detection of abnormal wear patterns and potential mechanical failures. ICP-OES, for instance, excites atoms in a plasma and measures emitted light at specific wavelengths, providing a detailed breakdown of metal concentrations in ATF samples. Similarly, XRF enables rapid, non-destructive elemental analysis, making it useful for monitoring fluid degradation trends over time.

By integrating regular elemental analysis into ATF maintenance practices, automotive technicians and researchers can proactively diagnose transmission issues, optimize ATF replacement schedules, and extend gearbox lifespan. This approach enhances vehicle reliability while minimizing costly repairs due to unexpected transmission failures. Table 2.5 shows the elements detected by Spectroil Q100.

Table 2.5
Elements detected by Spectroil Q100 (source: ASTM International)

Element	Symbol	Element	Symbol	Element	Symbol
Aluminium	Al	Magnesium	Mg	Vanadium	V
Barium	Ba	Manganese	Mn	Zinc	Zn
Boron	B	Molybdenum	Mo	Lithium	Li
Cadmium	Cd	Nickel	Ni	Antimony	Sb
Calcium	Ca	Phosphorus	P	Bismuth	Bi
Carbon	C	Potassium	K	Arsenic	As
Chromium	Cr	Silicon	Si	Indium	In
Copper	Cu	Silver	Ag	Cobalt	Co
Hydrogen	H	Sodium	Na	Zirconium	Zr
Iron	Fe	Tin	Sn	Tungsten	W
Lead	Pb	Titanium	Ti	Cerium	Ce

2.5.1.2 Viscosity

The viscosity test was conducted to evaluate the stability of ATFs under varying temperatures, as viscosity plays a crucial role in lubrication, heat dissipation, and overall transmission performance. Results showed that fluids with a high viscosity index (VI) maintained more consistent viscosity across temperature ranges, ensuring reliable lubrication in both cold and hot conditions. In contrast, fluids with a low VI experienced significant viscosity drop at higher temperatures, which may reduce film strength and increase wear risk. These findings highlight the importance of selecting ATFs with higher VI values to ensure better protection, efficiency, and durability of transmission systems under different operating environments.

A viscometer is a device used to measure the viscosity of a fluid, which represents its resistance to flow. For fluids with viscosities that change under varying flow conditions, a rheometer is used. A rheometer is essentially a specialized type of viscometer designed for complex flow behaviours (Barnes, 1989). In contrast, viscometers are limited to measuring viscosity under a single flow scenario.

The principle of a viscometer involves either moving an object through a stationary fluid or allowing a fluid to flow past a stationary object. The viscosity of the fluid is determined by measuring the drag force generated as the surface moves relative to the fluid. Accurate measurements require laminar flow conditions, which occur when the Reynolds number is low enough to prevent turbulence.

There are various types of viscometers, each tailored for specific applications. Capillary viscometers measure the time a fluid takes to flow through a narrow tube under gravity, making them ideal for low-viscosity fluids (Kestin et al., 1973). Rotational viscometers, on the other hand, use a spindle immersed in the fluid to measure torque and are suitable for a wide viscosity range (Powell, 1998). Falling ball viscometers determine viscosity by tracking the time it takes for a ball to fall through the fluid (Brizard et al., 2005), while (Brizard et al., 2005) rely on oscillating probes to gauge the damping effect of the fluid, often used for real-time industrial monitoring (AKPEK et al., 2014). The types of viscometers were shown in Figure 2.1.

(a) (b) (c)

Figure 2.1 (a) Capillary Viscometer (b) Rotational Viscometer (c) Falling Ball Viscometer

Viscometers have diverse applications across industries. In the automotive sector, they are critical for evaluating the viscosity of lubricants, fuels, and transmission fluids to ensure optimal performance. In the pharmaceutical and food industries, viscometers ensure product quality and consistency, such as in liquid formulations or syrups. Similarly, they are employed in petrochemicals for analysing crude oil and in cosmetics for maintaining the desired texture of products like creams and gels.

Understanding a fluid's viscosity is essential for optimizing its performance in practical applications. For instance, maintaining the correct viscosity in automotive lubricants minimizes wear, enhances efficiency, and extends the lifespan of mechanical components. In industries such as pharmaceuticals and food production, precise viscosity control is crucial for ensuring product stability and a satisfactory user experience.

2.5.1.3 Fourier Transform Infrared (FTIR)

Fourier-transform infrared spectroscopy (FTIR) is a technique used to obtain the infrared spectrum of absorption or emission of a material (Griffiths & Haseth, 2007). This method is widely applied to identify chemical bonds and molecular structures within a sample. An FTIR spectrometer collects high-resolution spectral data across a broad spectral range simultaneously, providing a significant advantage over traditional dispersive spectrometers, which measure intensity over a narrow range of wavelengths at a time.

The core principle of FTIR involves the use of an interferometer, which modulates the infrared light to generate an interferogram. This raw data is then processed through a mathematical operation called the Fourier transform, converting the interferogram into a detailed spectrum. The resulting spectrum provides insights into the chemical composition of the sample by identifying characteristic absorption bands corresponding to specific molecular vibrations (Hook & Kahle, 1996).

FTIR spectroscopy is extensively used in various fields due to its versatility and efficiency. In materials science, it helps analyse polymers, coatings, and composites. In the pharmaceutical industry, it is employed to identify active ingredients and monitor the quality of formulations. FTIR also finds applications in environmental science for detecting pollutants in air and water and in the food industry for assessing product quality and detecting adulterants.

The ability of FTIR to provide rapid and non-destructive analysis, along with its high sensitivity and broad applicability, makes it a powerful tool for both qualitative and quantitative analyses. Table 2.5 shows the spectral location of the components, and Table 2.6 shows the comparison on the graph spectrum.

Table 2.6

The spectral location of the components.

Component	Spectral Location	Measurement	Traditional Measurement	Sensitivity
Soot	2000	Carbon Load	Total Insolubles	Insensitive
Oxidation	1750	Oil Degradation	BN, AN, Viscosity	Partially
Nitration	1630	Oil Degradation	BN, AN, Viscosity	Partially
Sulfation	1150	Oil Degradation	BN, AN, Viscosity	Partially
Water	3400	Contaminant	Karl Fischer	Partially
Glycol	1040	Contaminant	Gas Chromatography (GC)	Very
Diesel	800	Contaminant	Flash Point, Viscosity, GC	Extremely
Gasoline	750	Contaminant	Flash Point, Viscosity, GC	Extremely
ZDDP (AW)	980	Additive	Elemental Spectroscopy	Extremely

The FTIR spectrum of a mixture of a synthetic oil based on polyalphaolefins and an electro-hydraulic control (EHC) fluid with phosphate ester is shown in Figure 2.3 below as an example of FTIR test result.

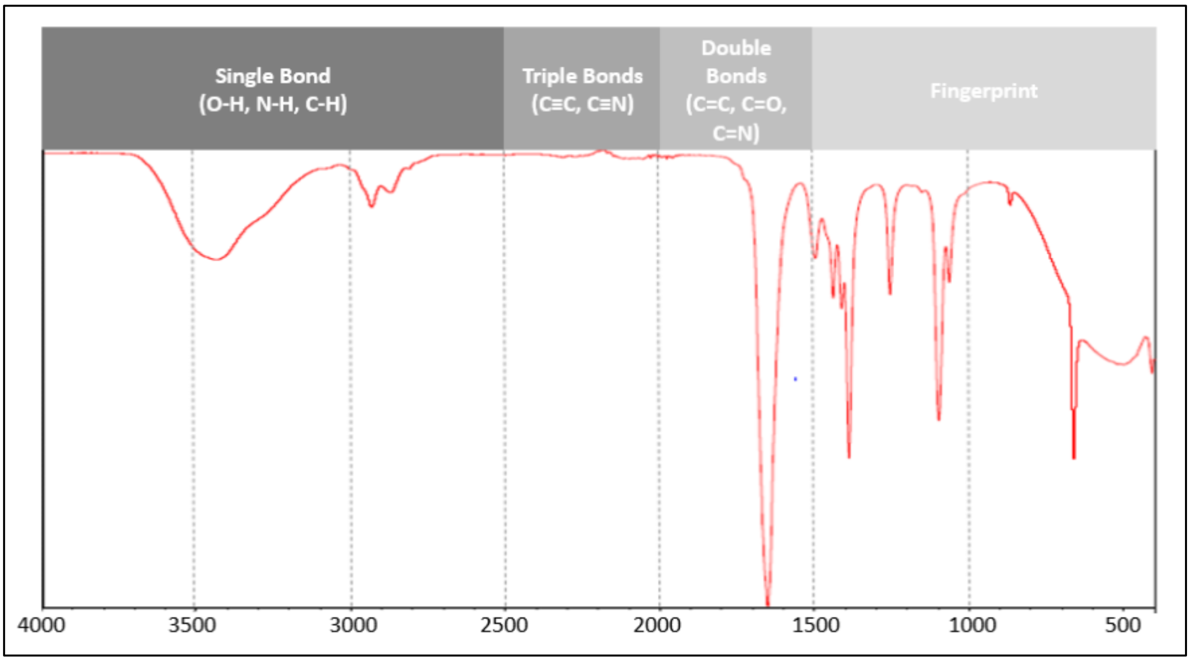


Figure 2.2 FTIR Spectrum Region

Source: (Nandiyanto et al., 2019)

Oil analysis and end users can gather a lot of information by combining the methodology with other conventional test methods and tactics and by being aware of its workings as well as its advantages and disadvantages.

2.5.2 Tribological Properties of ATF from Other Researchers

A fluid film between two moving surfaces must exist and is highly dependent on the viscosity of the fluid (Hamid & Daud, 2015). Increased sliding, particularly metal-to-metal contact between two surfaces, can lead to higher viscosity and friction. Since the advent of the automobile, transmission oils have been extensively utilized to address this issue. This is because sliding surfaces in a transmission system frequently encounter one another during operation. To prevent metal-to-metal contact, reduce friction, and inhibit corrosion, proper lubrication is essential (Mike Johnson CLS, 2008). Furthermore, it facilitates cooling of the transmission system and heat dissipation, which reduces power loss and enhances fuel efficiency.

Modern ATFs are engineered with advanced additives to optimize their tribological performance. These additives include friction modifiers, anti-wear agents, and corrosion inhibitors, which improve the oil's ability to maintain a consistent film between contacting surfaces under various operating conditions. The chemical composition of ATFs also provides high thermal stability, ensuring that the fluid maintains its performance characteristics under extreme temperatures and heavy-duty operations (Di et al., 2023; Kamis et al., 2024; Zechao et al., 2023).

During the clutch running-in process, the friction-wear performance is significantly influenced by the ATF temperature. As the ATF temperature increases, the mean coefficient of friction decreases and drops rapidly during the first 60 or so clutch engagements. The rise in ATF temperature causes the fluid film to become thinner, leading to more asperity peaks being sheared, resulting in a smoother surface. Maintaining an appropriate ATF temperature is crucial to ensure minimal immediate friction fluctuations and optimal wear performance.

ATF plays a critical role in ensuring smooth gear shifting by reducing shock and vibration within the transmission system. The fluid's ability to absorb and dissipate energy during gear changes contributes to improved vehicle drivability and longevity of the transmission components (Taylor et al., 2005; Zulkifli et al., 2013). Furthermore, ATF enhances sealing efficiency within the transmission, preventing fluid leaks and maintaining optimal pressure levels for effective operation.

The development of synthetic ATFs has further expanded the tribological capabilities of these fluids. Synthetic formulations exhibit superior shear stability, oxidation resistance, and low-temperature fluidity compared to conventional ATFs. These properties enable extended service intervals and improved performance in modern high-efficiency transmission systems.

Table 2.7
Summary of Tribology Findings

Author / Year	Study Focus	Method / Test Used	Key Findings	Research Limitation
Spikes (1996)	Friction behaviour of automatic transmission fluids	Tribological friction tests on wet clutch systems	Friction modifiers stabilize the coefficient of friction and reduce friction fluctuation during clutch engagement	Focused on fresh ATF formulation rather than restoration of used ATF
Canter (1997)	ATF additive technology and formulation	Lubricant formulation analysis and tribological testing	Additive packages such as friction modifiers, detergents, and anti-wear agents play a major role in maintaining friction performance	Limited discussion on additive replenishment for degraded ATF
Muraki (2002)	Influence of friction modifiers in ATF	Boundary lubrication tribological tests	Surface-active additives form protective layers that improve lubrication and reduce wear	Study focused on additive chemistry rather than treatment oil application
Fan et al. (2022)	Tribochemical behaviour of friction modifiers in ATF	Tribometer test and surface analysis	Formation of calcium hydroxyphosphate tribofilms improves lubrication stability and friction performance	Study examined additive interaction but not restoration of used ATF
Abdullah et al. (2019)	Tribological performance of commercial ATF	Disc-on-disc tribometer friction analysis	Stable tribofilm formation influences friction behaviour and anti-shudder performance	Focused on ATF formulation rather than treatment oil effectiveness
Present Study	Restoration of used ATF using treatment oil	Reciprocating tribological test measuring Coefficient of Friction (CoF)	Evaluates friction performance of used ATF before and after treatment oil addition	Provides experimental data on friction restoration behaviour

2.6 Concluding Remarks

This chapter reviewed the fundamental principles of tribology, including friction, wear, and lubrication, which form the theoretical basis for understanding the performance of ATFs in transmission systems. It discussed the functions, properties, composition, and additive chemistry of ATF, emphasizing its roles in ensuring friction stability, wear protection, thermal control, and oxidative resistance under severe operating conditions. The mechanisms of ATF degradation and associated performance loss were examined, highlighting the technical and environmental need for effective restoration strategies. Treatment oils were analysed in terms of its purpose, composition, and mechanisms of action in restoring used ATF, alongside current challenges related to compatibility, stability, and long-term performance. Key characterization techniques, including elemental, physicochemical, and tribological analyses, were also reviewed as essential tools for evaluating ATF quality and treatment effectiveness. Past studies have mostly been descriptive, with little comparison between methods and inconsistent results on the effectiveness of treatment oils in restoring used ATF. Systematic testing of commercial treatment oils under standard conditions is lacking, and the connection between treatment methods and performance recovery is not well understood. This highlights the need for a clear and consistent approach to evaluate and improve ATF restoration. This research contributes by developing and testing an optimized ATF treatment method, combining physical, chemical, and tribological analyses, and showing how treatment parameters affect performance, providing a practical framework for sustainable ATF regeneration while addressing gaps in previous studies.

CHAPTER 3
RESEARCH METHODOLOGY

3.1 Introduction

This research is dedicated to investigating the tribological effects of treatment oil in ATF. Within this chapter, a comprehensive overview of the proposed research methodology is presented, encompassing key stages from the selection of ATF samples and the execution of tribological tests to the intricacies of oil formulation and the subsequent verification process. Additionally, attention is given to the careful consideration of experimental parameters, data collection techniques, and the robust analysis of results, ensuring a thorough and insightful exploration of the treatment oil's impact on tribological performance of an ATF.

3.1.1 Research Flow

The research methodology adopted in this study is illustrated in Figure 3.1 and is divided into three main stages. The first stage involved sample collection, which comprised five fresh ATF samples from different providers (designated as reference ATFs) and two used ATF samples collected after 20,000 km of service. The fresh ATF samples were analysed for their elemental and physicochemical properties, based on which two ATF brands were selected for further investigation. Corresponding used ATF samples of the same brands, each with 20,000 km mileage, were then identified. At this stage, treated ATFs were also prepared by blending the used ATF samples with treatment oil. In the second stage, tests of physicochemical properties, including viscosity measurement, elemental analysis, and Fourier Transform Infrared Spectroscopy (FT-IR), were carried out on the fresh, used, and treated ATFs. Tribological tests were also conducted to evaluate anti-wear and extreme pressure characteristics. The physicochemical and tribological properties of the used and treated ATFs were then compared with those of the fresh (reference) ATFs. Finally, in the third stage, the complete technical specifications of the treated ATFs were established.

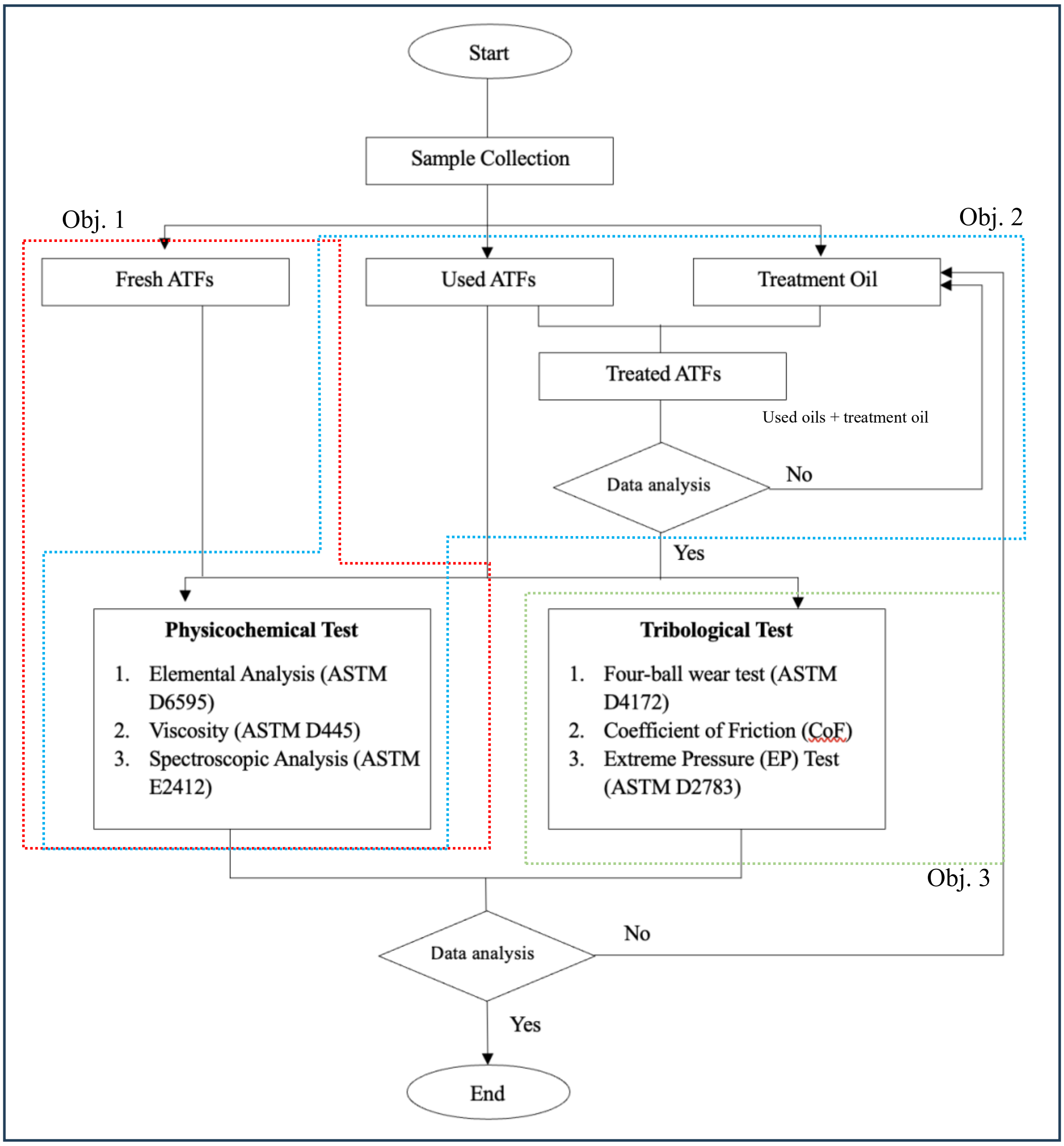


Figure 3.1 Flow of Research Methodology

3.2 Sample Preparation of Fresh ATFs, Used ATFs and Treated ATFs.

The sample collection began with gathering five types of ATFs from different brands but with same grade, Dexron III. The fresh ATFs are labelled as ATF A_0 , B_0 , C_0 , D_0 and E_0. Using fluids of the same grade ensures consistency in specification, while the different brands capture variations in additive formulation that may influence performance. Two used ATF samples from ATF A_0 and B_0 after 20,000km mileage was also collected, and labelled as ATF A and B to proceed in the next stage. ATF A and B represent two of the most commonly available and widely used commercial brands in the local market. The selection was made to enhance the practical relevance and external validity of the study, ensuring that the findings reflect real-world usage conditions rather than niche or less representative products. The used ATF was filtered to remove contaminants like metal particles or debris that might interfere with the blending process. The treatment oil in this study is provided by JV Auto Lube Sdn. Bhd. The treatment oil was measured 4 vol.%, according to the recommended concentration, typically specified by the manufacturer. The used ATFs (ATF A and B) have then been added with treatment oil and labelled as ATF A_1 and B_1. The process of making treated ATFs was shown in Figure 3.2 and a summary of all materials is summarized in Table 3.1.

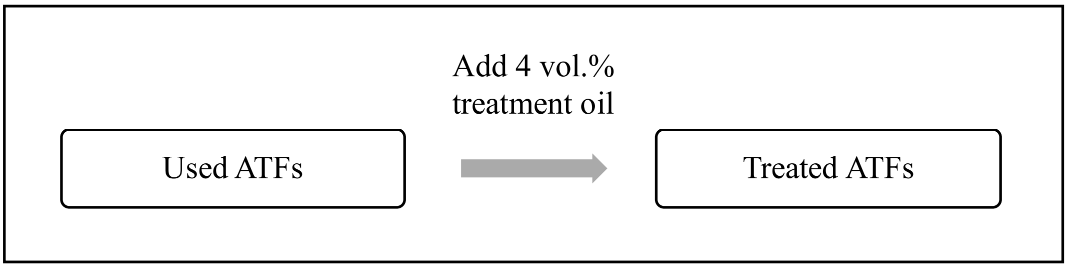


Figure 3.2 Process of Making Treated ATFs

Table 3.1
Samples material

Samples	Number of Samples	Label
Fresh ATFs (reference oils)	5	ATF A_0, B_0, C_0, D_0 and E_0
Treatment Oil	1	None (added in used ATF)
Used ATFs	2	ATF A and B
Treated ATFs	2	ATF A_1 and B_1

The oil treatment contained detergent, anti-seize, extreme pressure (EP), anti-foam, and anti-wear additives. The samples of used ATF A and B were mixed with 4 vol.% of the treatment oil, as suggested by the manufacturer, and labelled as ATF A_1 and B_1 respectively. The blending process involves gradually introducing the treatment oil into the used ATF while stirring continuously to ensure uniform dispersion of the additives. In addition to mechanical mixing, the samples undergo an ultrasonication process. The transmission treatment additives were mixed into the ATFs using the ultrasonication method for 30 minutes at 75˚C (Shaari et al., 2015). After blending, the mixture is allowed to rest for an hour to enable the additives to fully integrate into the ATFs. The homogeneity of the treated samples was verified through visual inspection and short-term stability observation. No visible sedimentation, phase separation, or turbidity differences were observed, indicating uniform dispersion of the additives within the base fluid. Figure 3.2 shows only the samples of ATF A as ATF B also shows the same results.

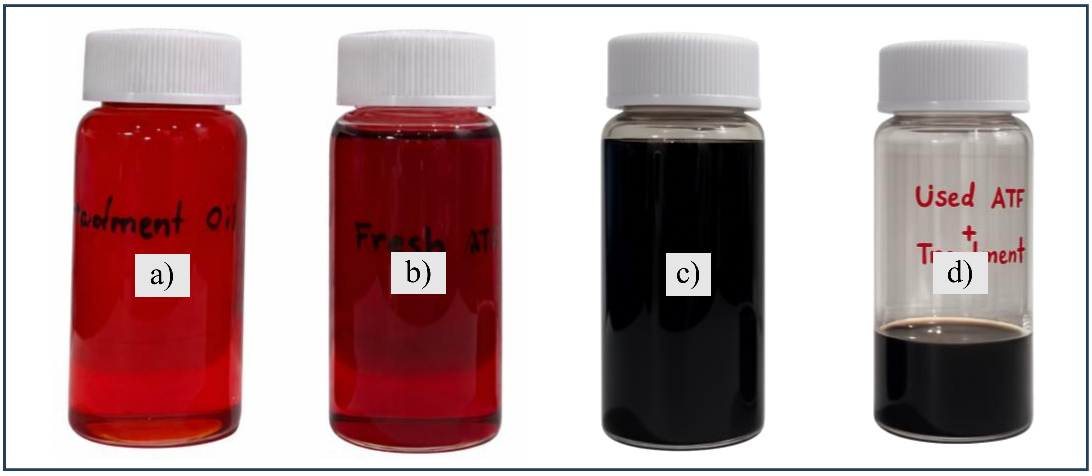


Figure 3.3 a) Treatment Oil, b) Fresh ATF A_0, c) Used ATF A, d) Treated ATF A_1

3.3 Physiochemical Properties Tests

The physicochemical properties of ATF refer to the physical and chemical characteristics that define its behaviour and performance. To gain a deeper understanding of their properties, viscosity tests, elemental analysis and Fourier Transform Infrared (FT-IR) Spectroscopy tests following the ASTM standard mentioned in Table 3.2 were conducted to verify and supplement the available information. The tests were selected because each measures critical indicators of ATF degradation, which are lubrication behaviour, wear metals or additive content, and chemical changes. These three methods efficiently capture both physical and chemical degradation relevant to transmission performance.

Table 3.2
ATF properties testing

Properties	ASTM Standard	Machine
Elemental Analysis	ASTM D6595	Spectroil Q100
Viscosity	ASTM D445	Cannon-Fenske Viscometer
FT-IR	ASTM E2412	FTIR spectrometer

3.3.1 Elemental Analysis

Elemental analysis was performed using the Spectroil Q100, an atomic emission spectrometer, as shown in Figure 3.5, to detect the elements present in ATFs. The test conforms to ASTM D6595, allowing the detection of a total of 33 metal and non-metal elements in the parts per million (ppm) range. In practice, an ATF sample was applied to the lens surface and then burnt in the spectrometer. The test was repeated five times for each sample to ensure result accuracy. Based on the results obtained, the major elements in the ATFS were identified to estimate the types of additives used in the formulations.

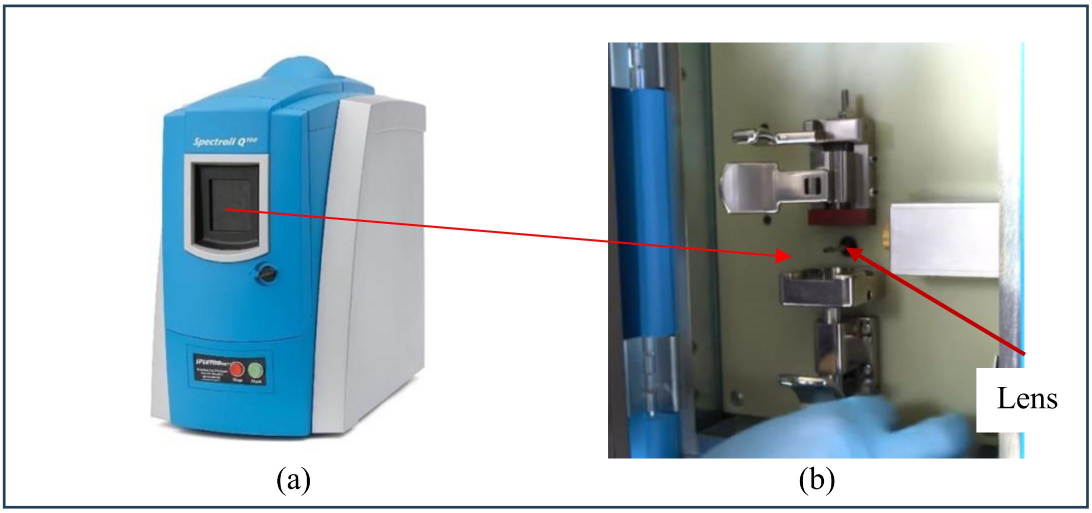


Figure 3.4 (a) The Spectroil Q100 spectrometer, and (b) Test specimen inside the spectrometer.

3.3.2 Viscosity

The kinematic viscosity of the samples was measured using a viscometer as shown in Figure 3.5. For this study, the tests were conducted at temperatures from 40°C to 100°C, increasing in 10°C increments, to reflect conditions typical of transmission and major component operation. A graph of temperature versus kinematic viscosity was plotted to analyse their relationship. The viscometer bath and U-tube inside the viscometer bath are shown in Figure 3.4

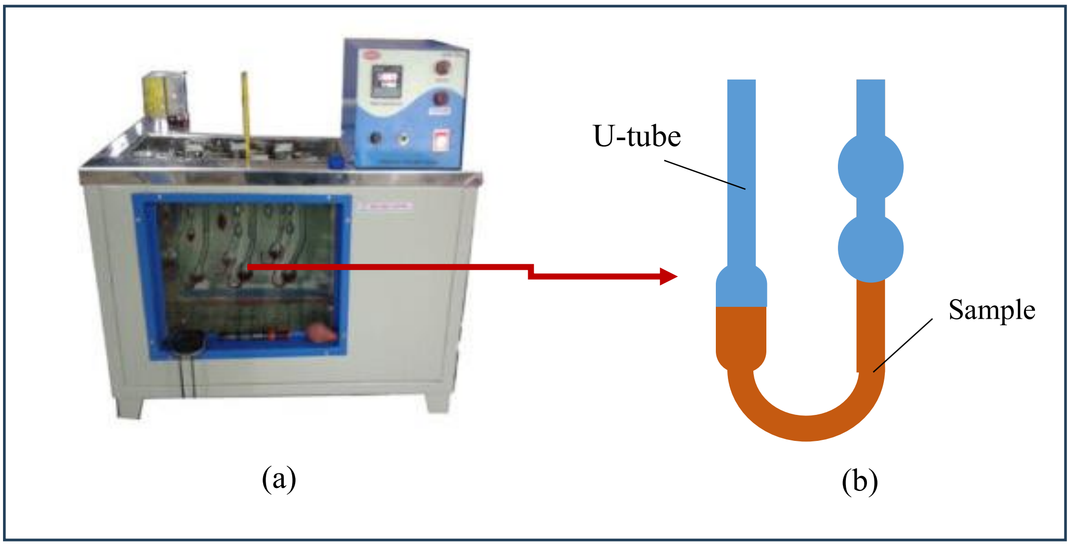


Figure 3.5 (a) The viscometer bath, and (b) The U-tube inside the viscometer bath

3.3.3 FT-IR Analysis

The Fourier Transform Infrared Spectroscopy (FT-IR) analysis began with the preparation of ATF samples following ASTM E2412 to identify oxidation products and additive degradation. The prepared samples were then placed in the FTIR spectrometer, where infrared radiation was passed through them to generate an absorption spectrum as shown in Figure 3.6. This spectrum, representing the unique molecular fingerprint of each sample, was recorded and analysed to identify specific chemical bonds, additives, and functional groups present in the ATFs. The findings were then cross-referenced with known spectra to verify the additives and bonding within the samples.

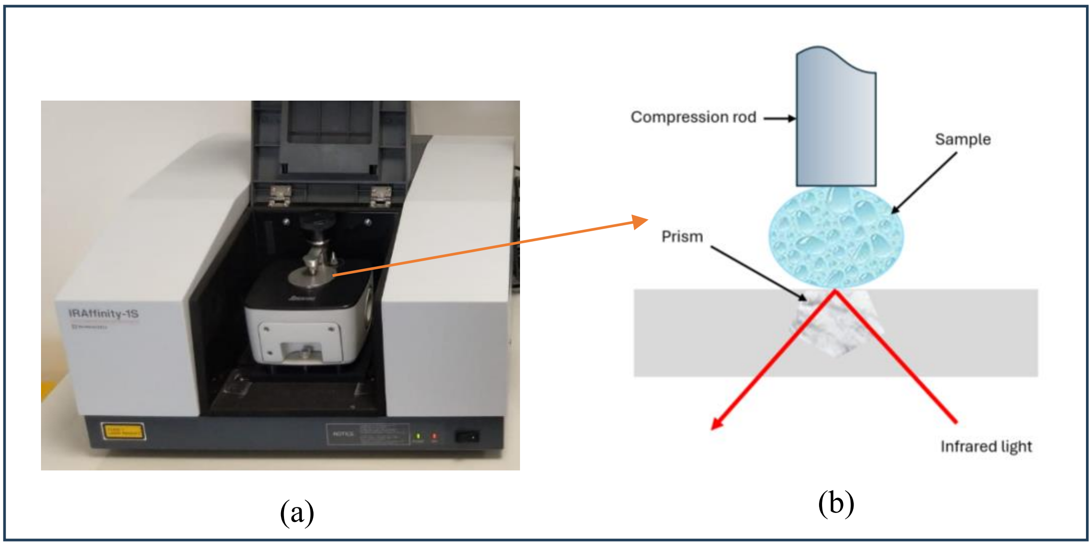


Figure 3.6 (a) FTIR Machine, and (b) A schematic diagram of the optical system

3.4 Tribological Properties Tests

In the current work, the friction and wear profiles were to be determined to explore the tribological characteristics of the ATF samples. For that purpose, four ball wear testers were carried out.

3.4.1 Wear Preventive (WP) Measurement

The wear-preventive properties of the ATF samples were evaluated using the four-ball wear test in accordance with ASTM D4172. In this method, a rotating steel ball is pressed against three stationary steel balls immersed in the lubricant sample, providing a standardized assessment of the fluid's ability to minimize friction and wear under controlled conditions.

The selected test parameters (load, rotational speed, temperature, and duration) were chosen based on ASTM D4172 standard conditions to represent boundary lubrication regimes commonly encountered in automatic transmission clutch packs and gear contacts. The applied load generates sufficient contact stress to promote asperity interaction and boundary film formation, while the selected temperature reflects moderate operating conditions of transmission fluids during service. The test duration was determined to allow measurable wear scar development without inducing severe scuffing, ensuring reliable comparison between fresh, used, and treated ATF samples.

After the test, the average Wear Scar Diameter (WSD) on the steel balls was measured microscopically, with smaller WSD values indicating better anti-wear protection. Differences in WSD values were correlated with the elemental composition and the presence of tribo-film-forming additives such as phosphorus, zinc, calcium, and boron, providing mechanistic insight into the anti-wear performance of each formulation. This measurement not only reflects the lubricant's effectiveness in preventing metal-to-metal contact but also highlights differences between commercial ATFs that have not been systematically compared in previous studies. The key test conditions (load, speed, temperature, and duration) are summarized in Table 3.3. Additionally, the frictional behaviour recorded during the test provides insight into boundary film formation and lubricant film stability, addressing the lack of comprehensive tribological evaluation in used ATFs and helping to identify potential limitations in current formulations.

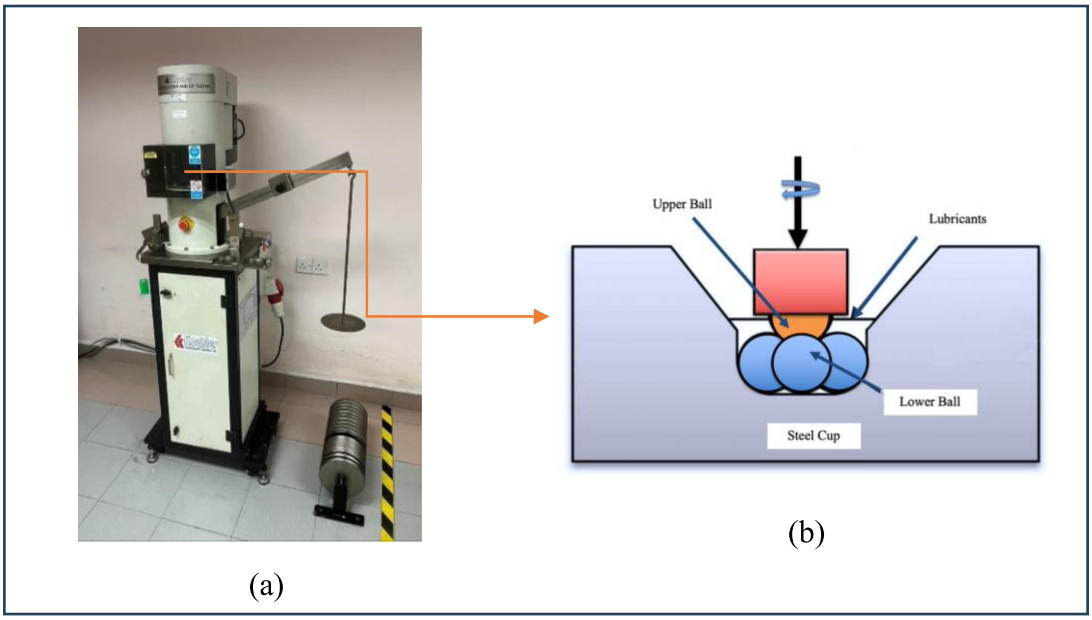


Figure 3.7 (a) The four-ball wear tester, and (b) the four-ball assembly

Table 3.3
Test parameters for the WP

Parameter	WP (ASTM D4172)
Rotating speed (rpm)	1200 ± 60
Temperature (ºC)	75 ± 2
Duration	60±1 min
Load (kgf)	40

3.4.2 Extreme Pressure (EP) Measurement

The extreme-pressure performance of the ATF samples was determined using the four-ball EP test according to ASTM D2783. This test evaluates the lubricant's ability to withstand increasing contact pressures before welding or surface failure occurs.

The applied load is increased stepwise until welding takes place between the balls. From these data, the Load-Wear Index (LWI) and Weld Point are determined, which describe the lubricant's resistance to scuffing, seizure, and adhesive wear under severe conditions. The detailed test sequence and conditions are presented in Table 3.4.

Table 3.4
Test parameters for the EP

Parameter	EP (ASTM D2783)
Rotating speed (rpm)	1760 ± 40
Temperature (ºC)	27 ± 8
Duration	Series of 10 sec
Load (kgf)	As per standard

3.5 Concluding Remarks

Overall, this chapter explains the research methods that have been carried out in this study in achieving the stated research objectives. The methodology as presented is experimental based and verified with properties of the commercially available ATFs. It involves stages of collecting and preparation process for the samples and extensive testing and analysis. The results and analyses are presented in the following chapter.

CHAPTER 4
RESULTS AND DISCUSSION

4.1 Introduction

This chapter presents the results and findings of this study. The analysis focuses on evaluating the properties of fresh ATF, understanding the degradation behaviour of ATF after 20,000 km of service, and assessing the effectiveness of adding 4 vol.% treatment oil. The findings were compared between fresh, used, and treated ATF, and are presented sequentially according to each stage of the ATF preparation process, with discussion supported by relevant literature.

4.2 Homogeneity of Used ATFs with Treatment Oil

The blended used ATFs with treatment oil are shown in Figure 4.1. Two samples were prepared, namely ATF A_1 and ATF B_1. Both samples exhibited similar visual characteristics throughout the observation period. The samples were observed on Day 1, Day 2, Day 7, and Day 14 to monitor any visible changes. Throughout the observation period, no clear separation, sedimentation, or formation of solid residues was detected in the samples. The colour and appearance remained generally consistent, with no noticeable layer formation.

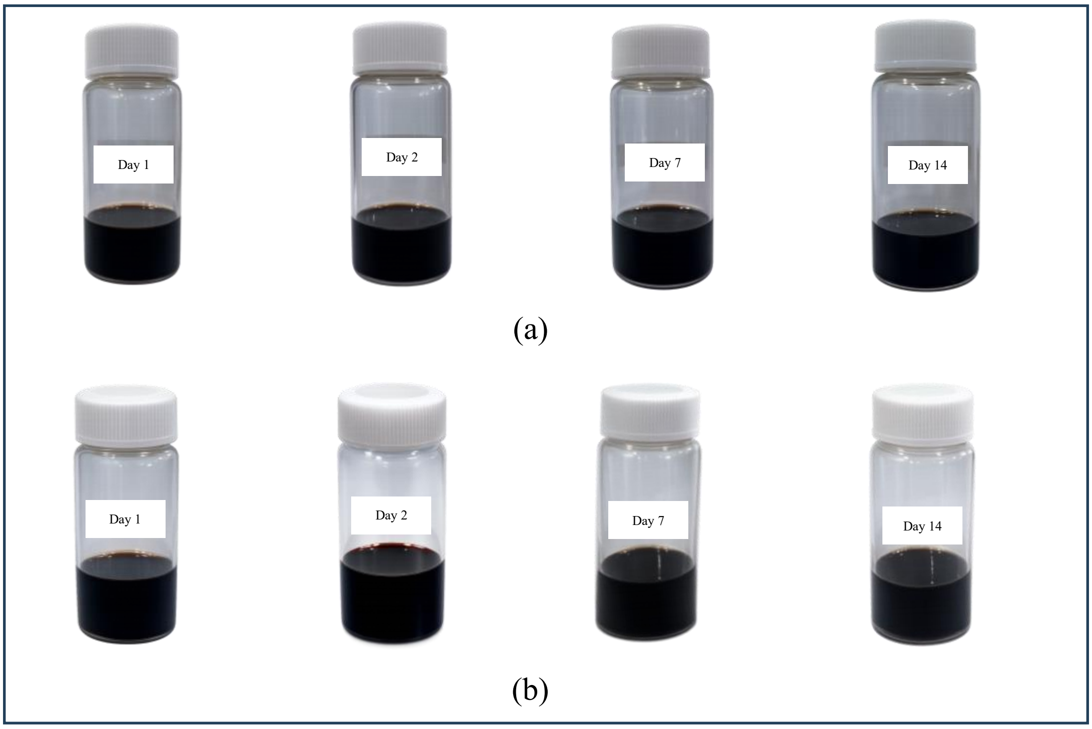


Figure 4.1 The samples observation of (a) ATF A1 and (b) ATF B1

4.3 Physiochemical Properties of Fresh ATFs, Used ATFs and Treated ATFs

4.3.1 Composition of Fresh ATFs, Used ATFs and Treated ATFs

The presence and composition of elements in fresh ATFs were determined by elemental analysis using a Spectroil Q100 analyser. Based on the detected elements, the degradation of additives and base oil in the ATFs could be assessed. Table 4.1 presents the elemental composition of the fresh ATFs in parts per million (ppm). Each additive in an ATF formulation plays a distinct functional role, whether as an anti-wear agent, detergent, antioxidant, anti-foam compound, or extreme pressure (EP) modifier, contributing to the overall durability and performance of the transmission system.

Anti-wear elements identified across various fresh ATF samples include boron (B), phosphorus (P), zinc (Zn), and zirconium (Zr), which are commonly associated with the formation of protective tribo-films (Akbiyik et al., 2022; Alias et al., 2018; Mistry et al., 2013; Thachnatharen et al., 2022; W. Wang et al., n.d.; Zhao et al., 2014).Boron and phosphorus were consistently detected in multiple formulations, underscoring their widespread use in minimizing friction and mechanical wear. Zirconium, however, was only present in ATF A_0, indicating that its inclusion may be limited to niche or high-performance formulations.

Calcium (Ca) and magnesium (Mg) function as detergent additives, essential for maintaining transmission cleanliness by neutralizing acidic byproducts and inhibiting deposit formation. Calcium was detected in all samples, whereas magnesium was exclusive to ATF B_0, D_0, and E_0, suggesting it is selectively incorporated based on formulation targets. The synergistic action between Ca and Mg enhances deposit control and overall system hygiene (Gao et al., 2018).

Referring to Table 4.1, the presence of molybdenum (Mo) solely in ATF D_0 is notable, as this element is widely recognized for its extreme pressure resistance and low-friction characteristics. Its inclusion suggests that ATF D_0 is engineered for heavy-duty or high-load transmission environments (Parenago et al., 2017a). Silicon (Si), serving as an anti-foam additive, was found in ATF B_0 and E_0, where it plays a vital role in suppressing foam formation, thereby preserving fluid stability and preventing air entrapment during operation (J. Chen, 2010).

Table 4.1

The Elemental Composition Of The Reference Atfs In Parts Per Million (ppm).

		ATF A_0	**ATF B_0**	**ATF C_0**	**ATF D_0**	**ATF E_0**	**Treatment Oil**
		(ppm)	**(ppm)**	**(ppm)**	**(ppm)**	**(ppm)**	**(ppm)**
Common elements	Ca	3.01	287.52	49.394	104.23	246.36	18.45
	H	6839.1	6726.7	5696.6	6192.8	6864.8	8576.3
	C	22290	22918	20170	22065	233.92	21780
Difference in elements	As	-	14.76	-	-	22.34	-
	B	7.44	87.50	53.136	74.947	371.48	-
	Bi	-	-	2.04	-	-	-
	Fe	-	1.32	-	-	-	-
	In	-	-	1.917	-	-	-
	Mg	-	7.81	-	3.142	169.88	3.33
	Mo	-	-	-	2.801	-	-
	Na	-	-	-	26.784	-	-
	P	12.19	-	-	-	-	18.53
	Si	-	2.18	-	-	3.966	2.41
	Sr	-	-	16.507	3.478	-	-
	W	-	520.58	205.96	245.28	-	133.67
	Zr	681.61	-	1.908	-	-	-
	Zn	-	217.11	1.492	21.687	343.52	93.81

In the treatment oil, a balanced composition of functional additives is evident. For instance, calcium (18.45 ppm) and magnesium (3.33 ppm) are present in supporting roles as detergents, helping to maintain system cleanliness and neutralize acids. The co-existence of zinc (93.81 ppm) and phosphorus (18.53 ppm) indicates the likely presence of zinc dialkyldithiophosphate (ZDDP), a well-established anti-wear and antioxidant compound that protects metal surfaces under high-temperature and high-pressure conditions (Alias et al., 2018; Fatima et al., 2016)

The high concentration of tungsten (133.67 ppm) in the treatment oil shows its role as a high-performance friction modifier or wear-resistant additive, suitable for demanding or extended-use applications. On the other hand, silicon (2.41 ppm) contributes to anti-foaming performance by minimizing bubble formation, thereby ensuring consistent film coverage and lubrication stability (Sui et al., 2018).

The treatment oil also exhibits elevated levels of carbon (21,780 ppm) and hydrogen (8,576.3 ppm), reflecting the organic nature of its base oil and additive compounds. These elements contribute to thermal stability, energy efficiency, and lubricating capability, reinforcing the oil's suitability for modern high-performance transmissions.

A comparison of elemental concentrations between the treatment oil and fresh ATFs where treatment oil demonstrates a significantly higher concentration of Zn and W compared to ATF A_0 and B_0. Specifically, Zn in the treatment oil (93.81 ppm) is approximately 4.8 times greater than in ATF A_0 (19.66 ppm), indicating a stronger anti-wear additive presence (Fatima, Minami, et al., 2015; Zhao et al., 2014). Similarly, W (133.67 ppm) is absent in all fresh ATFs but dominant in the treatment oil, underscoring its targeted function for extended durability.

In contrast to the inconsistencies observed in some fresh ATF samples, the treatment oil exhibits a more controlled and well-balanced formulation. It contains essential additives at consistent, performance-oriented concentrations. Elevated levels of zinc (93.81 ppm) and phosphorus (18.53 ppm) indicate the presence of ZDDP compounds, which are known for its effectiveness in reducing friction and preventing wear (Akbari et al., 2016). The detection of tungsten (133.67 ppm), a less common yet highly effective anti-wear element, further highlights the oil's suitability for high-load and high-temperature conditions. Additionally, calcium (18.45 ppm) and magnesium (3.33 ppm) function as detergents, contributing to internal cleanliness and the prevention of deposit buildup (Di et al., 2020a; Gao et al., 2018; Razak & Ahmad, 2021). The high concentrations of carbon (21,780 ppm) and hydrogen (8,576.3 ppm) reflect the oil's organic base and thermal stability, supporting long-term performance.

Unlike some fresh ATFs that contained contaminants such as arsenic (As), strontium (Sr), or bismuth (Bi), the treatment oil shows no signs of such impurities. This absence shows a high degree of quality control in its formulation and bottling, indicating that the treatment oil is not only chemically robust but also manufactured to consistently meet demanding operational standards. The treatment oil appears compatible with a range of ATF types, enhancing its performance when blended. Its balanced formulation and concentrated additive profile suggest synergistic effects when used as a supplement, potentially compensating for additive depletion in aged fluids. These findings support the treatment oil's design as a versatile, high-performance additive suitable for modern and legacy transmission systems alike.

The elemental analysis of the oil treatment with used ATFs shows the presence of key elements specifically selected to enhance performance and durability. Table 4.2shows the types of elements in ATF A_0, A, A_1, and ATF B_0, B, and B_1. Both ATFs consist of boron (B), calcium (Ca), phosphorus (P), hydrogen (H), and carbon (C) elements.

Table 4.2
Type of elements of samples ATF A and ATF B.

		ATF A_0 (ppm)	ATF A (ppm)	ATF A_1 (ppm)		ATF B_0 (ppm)	ATF B (ppm)	ATF B_1 (ppm)
Common elements	B	7.44	83.62	65.28	B	87.50	76.90	54.97
	Ca	3.01	49.80	48.67	Ca	287.52	78.53	71.54
	P	12.19	156.60	117.6	P	520.58	225.34	179.48
	H	6839.1	7034.6	6864.6	H	6726.7	6987.7	6883.4
	C	22290	23390	21739	C	22918	22852	21791
Elements presented in fresh ATFs	Zr	681.61	1.260	3.62				
					As	14.76	-	24.27
					Fe	1.32	66.74	52.08
					Mg	7.81	10.06	4.04
					Si	2.18	23.99	19.91
					Zn	217.11	16.89	10.31
Additional elements	Al	-	3.60	3.49	Al	-	50.17	43.059
					Ba	-	76.90	10.31
	Bi	-	2.08	-	Bi	-	5.00	-
	Cu	-	25.89	24.26	Cu	-	39.40	35.80
	Fe	-	38.54	32.25				
	Mg	-	4.09	3.51				
	Ni	-	3.94	3.71	Ni	-	5.32	3.52
	In	-	1.30	-				
					K	-	4.87	-
	Mo	-	1.32	-				
					Mn	-	7.59	4.91
					Na	-	5.87	4.33
	Si	-	5.41	4.71				
	Zn	-	26.33	15.27				
					Zr	-	-	3.46

Fresh ATFs (ATF A_0 and ATF B_0) serve as baselines, each containing essential elements for performance. ATF A_0 contains boron (B), calcium (Ca), phosphorus (P), and zirconium (Zr), while ATF B_0 includes arsenic (As), iron (Fe), magnesium (Mg), silicon (Si), zinc (Zn), and Ca, highlighting distinct differences in additive formulation and functional focus.

In used ATFs (after 20,000 km mileage), some elemental changes reflect the impact of wear, oxidation, and contamination. ATF A shows the presence of aluminium (Al), bismuth (Bi), copper (Cu), Fe, Mg, nickel (Ni), indium (In), molybdenum (Mo), lead (Pb), Si, and Zn, indicating increased metal wear and contamination. Similarly, ATF B displays additional elements such as Ba, K, Mn, Na, and Zr, which broader degradation and chemical changes due to extended service life. The presence of trace elements such as arsenic (As), indium (In), and bismuth (Bi) in used ATFs may result from either component wear, such as from solder alloys or coatings or contamination introduced during service, highlighting the complex interaction between lubricant chemistry and mechanical systems.

Used ATF with 4 vol.% oil additives (ATF A_1 and ATF B_1) significantly reduces the concentration of wear metals while preserving critical elements. In ATF A_1, levels of Cu (24.26 ppm) and Fe (32.25 ppm) are reduced compared to ATF A, indicating decreased wear. The additive also retains B, Ca, P, and Zr, suggesting restored or stabilized protection (Di et al., 2020b; R. N. Gupta & Harsha, 2016). ATF B_1 shows improved elemental stability and a notable reduction in harmful contaminants, supporting the treatment's efficacy in restoring fluid performance.

Elements such as boron (B), calcium (Ca), and phosphorus (P) are critical for tribofilm formation, which reduces friction and wear on contacting surfaces (Akbiyik et al., 2022; R. N. Gupta & Harsha, 2016; Mistry et al., 2013; Razak & Ahmad, 2021; W. Wang et al., 2018b). Comparing treated ATF A_1 with fresh ATF A_0, the concentrations of these key additives are partially restored, enabling formation of protective tribo-films that improve friction performance, although full recovery to A0 levels is not achieved due to irreversible base oil degradation.

ATF B_0's higher Ca (287.52 ppm) and P (520.58 ppm) content shows strong anti-wear and lubricating properties, while ATF A_0's lower Ca (2.96 ppm) and P (11.29 ppm) concentrations may correspond to a different additive philosophy or performance objective. Elevated Cu and Fe levels in used ATFs clearly indicate internal wear, emphasizing the importance of regular fluid monitoring and maintenance to avoid transmission damage. The ratio of calcium to phosphorus also plays a vital role in tribo-films stability. Higher Ca and P ratios, as seen in ATF B_0, may enhance deposit control and thermal stability, whereas balanced Zn and P levels support consistent anti-wear layer formation under high-pressure conditions.

The effectiveness of oil treatment is evident in the reduction of wear metals in treated samples. Both ATF A_1 and ATF B_1 show marked decreases in Cu and Fe levels, implying that the treatment not only mitigates ongoing degradation but also partially restores protective function. Additive elements such as phosphorus (P), zinc (Zn), and tungsten (W) likely contribute to this restoration. These elements are known to form tribo-films with anti-wear, antioxidant, and extreme-pressure properties (Alias et al., 2018; Fatima, Minami, et al., 2015; Parenago et al., 2017b), effectively reducing friction and prolonging component life.

Elemental analysis of fresh, used, and treated ATFs underscores the critical importance of fluid quality and maintenance. Fresh fluids offer essential protection through high concentrations of Ca and P, while used fluids accumulate wear metals, signifying performance degradation. Oil treatment helps reverse this trend by lowering contaminant levels and re-establishing protective additive films. Ultimately, maintaining a balance between fluid formulation, monitoring, and timely treatment is key to achieving long-term transmission reliability, reduced wear, and improved operational efficiency. These findings highlight the real-world value of periodic elemental analysis in predictive maintenance and product development.

4.3.2 Viscosity

The kinematic viscosity of the five fresh ATF samples at different temperature was shown in Figure 4.2. It shows distinct patterns in its viscosity profiles, which reflect how the fluids behave under different temperature conditions.

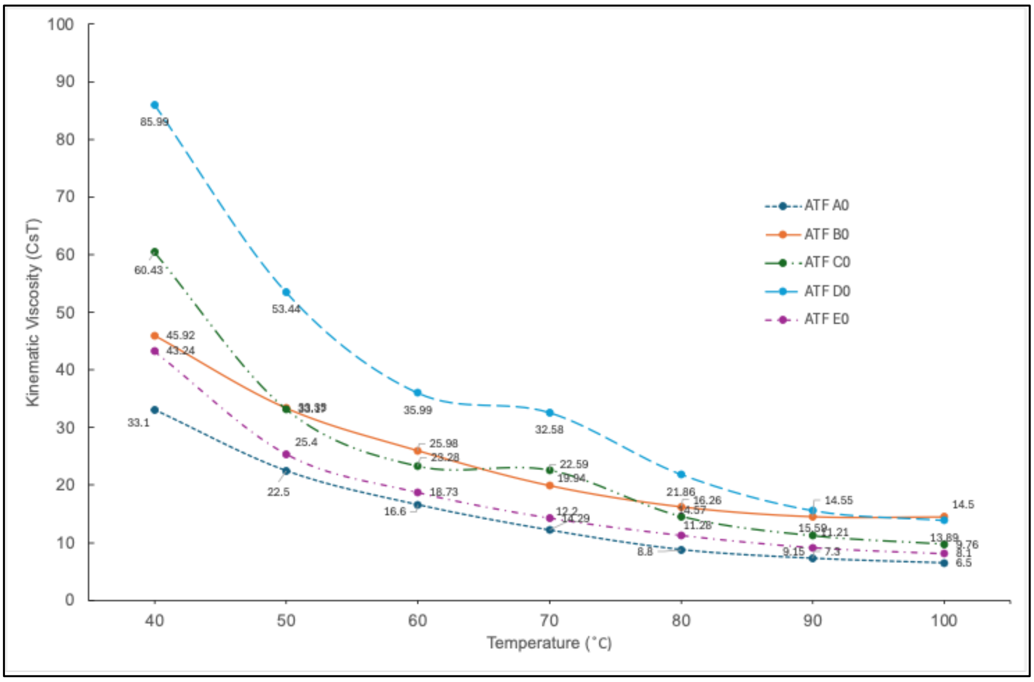


Figure 4.2 Variation of kinematic viscosity at different temperature of fresh ATF samples.

Referring to Figure 4.2, all ATF samples exhibit a gradual decrease with increasing temperature. ATF C_0 at 40°C exhibits a high viscosity of 60.43 cSt, which progressively drops to 9.76 cSt at 100°C. ATF C_0's graph profile shows a gradual, nearly linear drop in viscosity. This sharp in viscosity at higher temperatures means that ATF C_0 may become less effective as a lubricant as it warms up, which could result in more wear on gearbox parts in hot weather (Krantz & Kahraman, 2004; L. Tang et al., 2015).

In comparison to the other fluids, ATF D_0 shows greater viscosity at all temperatures. At 40°C, it is 85.99 cSt, and at 100°C, it drops to 13.89 cSt. In contrast to ATF C_0, the graph profile of ATF D_0 displays a more gradual slope and a similar linear decline. This smoother, more gradual viscosity decrease demonstrates that ATF D_0 provides more consistent lubrication and protection in transmissions operating at different temperatures by maintaining superior viscosity stability across the temperature range.

ATF E_0 stands out as having the lowest viscosity values across the temperature range, with 43.24 cSt at 40°C and 8.1 cSt at 100°C. ATF E_0 undergoes significant fluid thinning at high temperatures, as evidenced by the fact that its viscosity dramatically drops with temperature. This might lead to less lubrication and a higher chance of wear, particularly in gearbox systems that run hot for long stretches of time (Krantz & Kahraman, 2004). ATF E_0's graph displays a steep curve, suggesting that as temperature rises, the fluid's viscosity dramatically drops. This implies that ATF E_0 might not be as good at lubricating at higher temperatures, which would make it less appropriate for high-stress gearbox systems that need fluid properties that are stable over a broad temperature range.

At 40°C, ATF A_0's viscosity is 33.1 cSt, and at 100°C, it drops to 6.5 cSt. ATF A_0 exhibits a consistent decrease in viscosity, which is slightly slower than ATF E_0 but more noticeable than ATF A_0 at higher temperatures. The data indicates that although ATF A_0 maintains sufficient viscosity at lower temperatures, a more significant thinning of the fluid at higher temperatures may impair its performance. This might affect the fluid's capacity to offer sufficient lubrication and wear resistance in prolonged high-temperature situations.

ATF B_0 begins with a viscosity of 45.92 cSt at 40°C and ends with a viscosity of 14.5 cSt at 100°C. The fluid's viscosity steadily decreases, though not as sharply as in ATF C_0 and E_0. This demonstrates that ATF B_0 performs more steadily across a temperature range while retaining enough viscosity to shield gearbox components from higher temperatures. Similar to ATF D_0, ATF E_0's graph profile displays a slow, steady drop in viscosity, with a marginally higher viscosity at 100°C. This profile shows that ATF B_0 maintains a good balance between temperature stability and viscosity retention, performing consistently across the temperature range.

The Viscosity Index (VI) shown in Figure 4.3 is an important measure of a fluid's ability to maintain its viscosity across a range of temperatures. A high VI means the fluid's viscosity stays stable across temperature changes, while a low VI means the fluid thins out more quickly as temperature rises. From the calculated VI values, ATF C_0 exhibits the highest viscosity index, indicating excellent stability across a wide temperature range. This indicates that ATF C_0's viscosity changes very little in response to temperature changes, which makes it suitable for systems where reliable operation is essential. Although it is not as stable as ATF C_0, ATF B_0 likewise performs well in terms of viscosity stability, with a VI of 210.99. Although ATF E_0 (182.06) performs comparably to ATF C_0 and B_0, it is more vulnerable to changes in viscosity. When it comes to stability over temperature changes, ATF D0 ranks above ATF A_0 but below ATF E_0 with a VI of 163.48. With the lowest VI (129.51), ATF A_0's viscosity varies more dramatically with temperature, which may have an impact on performance in harsh operating environments.

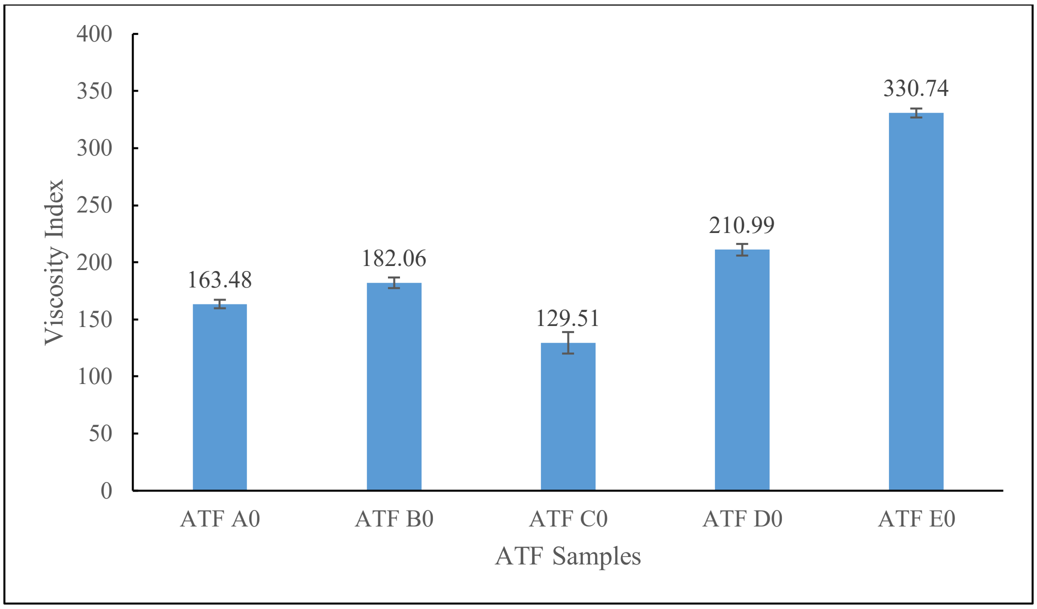
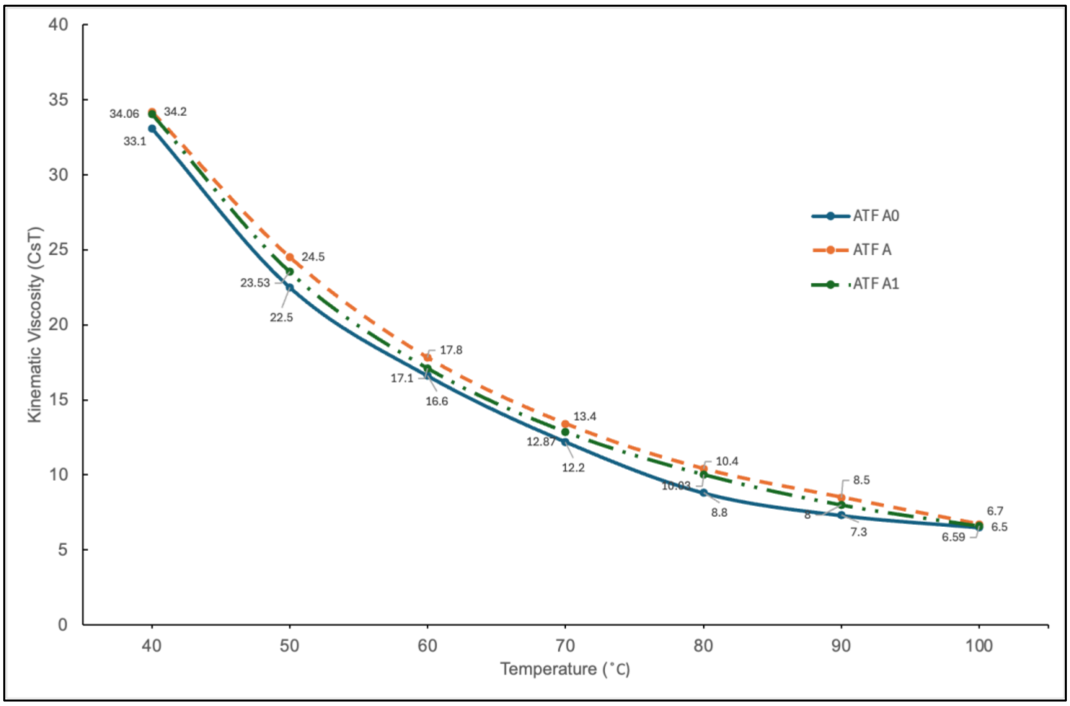


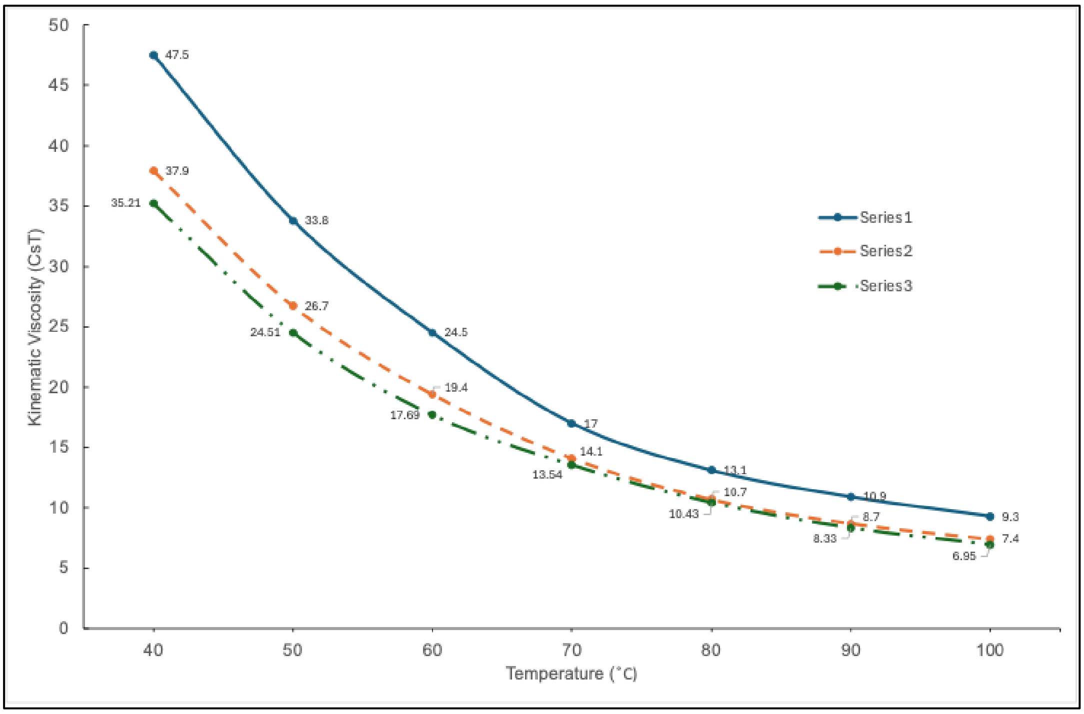
Figure 4.3 Viscosity Index (VI) of fresh ATFs samples

The VI does not always give a proper representation of the effect of temperature on the kinematic viscosity, as it does not account for shear stability, thermal degradation, or viscosity loss due to mechanical stress, all of which play crucial roles in real-world lubrication performance (Verdier et al., 2009). Therefore, relying solely on VI values may not provide a complete assessment of an ATF's effectiveness in demanding operating conditions.

The viscosity of the fresh, used and treated ATF A and B were shown in Figure 4.4 which was measured at various temperatures, ranging from 40°C to 100°C, in increments of 10°C, to assess its resistance to viscosity changes.



(a)



(b)

Figure 4.4 The kinematic viscosity of (a) ATF A and (b) ATF B

The kinematic viscosity data for the ATF A and ATF B, offers important information about the fluid's performance and state over time. ATF A_0's kinematic viscosity is 33.1 cSt at 40°C and steadily decreases to 6.5 cSt at 100°C as the temperature rises. This creates the baseline for comparison with the used ATF samples. The slightly higher viscosity observed in used ATF A (34.2 cSt at 40°C) correlates with the elemental analysis, which indicates the accumulation of wear metals such as Cu and Fe and the partial depletion of anti-wear additives like B, Ca, P, and Zr, reflecting oxidation, contamination, and additive degradation. The kinematic viscosity of treated ATF A_1 is 34.06 cSt at 40°C and drops to 6.59 cSt at 100°C. This treatment helps restore some additive functionality, stabilizing the fluid’s viscosity and contributing to the observed reduction in CoF due to enhanced tribofilm formation.

Fresh ATF B0 at 40°C has a viscosity of 61.85 cSt and drops to 7.96 cSt at 100°C, showing a high starting viscosity that dramatically declines with temperature, its high Ca and P concentrations support strong anti-wear and lubrication properties, which are reflected in its initial high viscosity and capacity to form stable tribo-0films. The viscosity of used ATF B at 20,000 km decreases to 14.5 cSt at 100°C after initially lower at 45.92 cSt at 40°C. This reduction aligns with the elemental findings showing additional contaminants such as Ba, K, Mn, Na, and Zr, which indicate degradation and altered lubrication behavior. The treated ATF B_1 has a viscosity of 37.66 cSt at 40°C and 11.09 cSt at 100°C. Although oil treatment partially restores additive activity, the viscosity profile suggests limited recovery, consistent with the elemental results where some wear metals persist and tribofilm formation is not fully optimal.

Both the ATF A and ATF B samples' viscosity graph profiles exhibit a linear decline with rising temperature. The initial viscosity differences between fresh, used, and treated ATFs reflect not only thermal effects but also chemical and elemental changes that influence lubricating film strength and friction performance. The initial viscosity of ATF A is lowest for fresh ATF A_0, slightly higher for used ATF A, and slightly lower but still comparable to treated used ATF A_1. Regarding ATF B, the used ATF B exhibits a moderate decline, the treated used ATF B_1 has little effect on the viscosity profile of used ATF, and the fresh ATF B_0 has the highest initial viscosity and steepest decline. These trends highlight how elemental composition, additive depletion, and oil treatment collectively affect viscosity, film formation, and tribological behaviour.

The viscosity index (VI) is a crucial indicator of an ATFs' ability to maintain consistent viscosity across varying temperatures. ATF A samples' kinematic viscosity does not significantly alter with temperature, but ATF B samples do. The viscosity index for samples ATF B and the kinematic viscosity curve at 40°C and 100°C are shown in Figure 4.5.

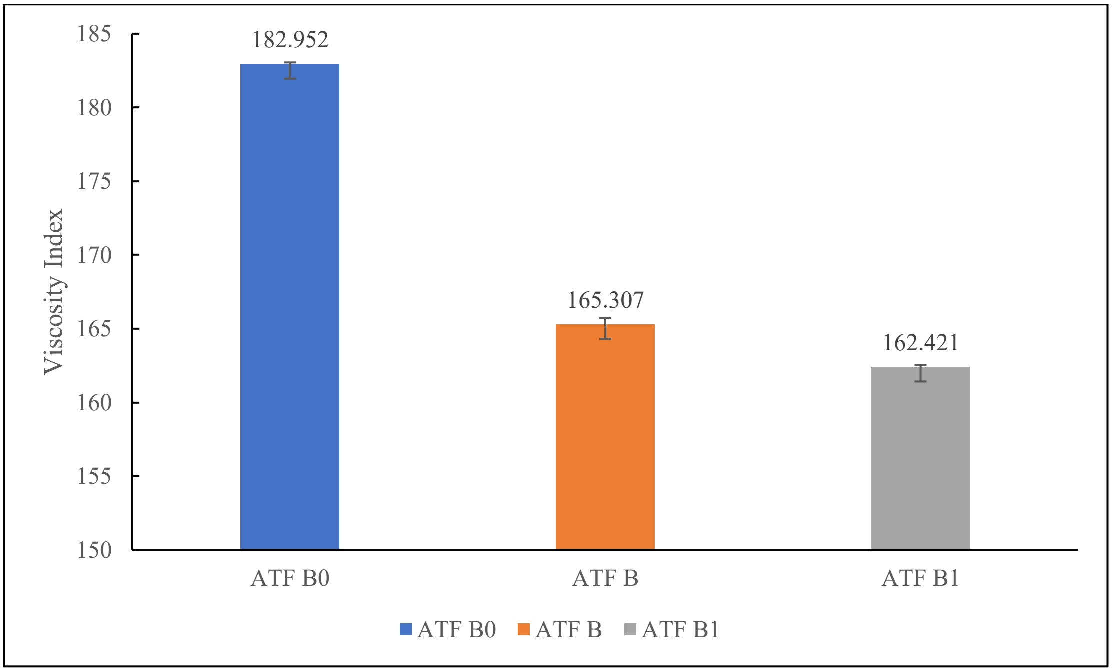


Figure 4.5 Graph of viscosity index (VI) and kinematic viscosity at 40°C and 100°C of ATF B

For ATF B_0, it starts with a higher VI of 182.95, indicating excellent viscosity stability. A higher viscosity index indicates less viscosity change with temperature, preferred for automotive engines due to better viscosity stability across temperature ranges (Boussaid et al., 2024). After 20,000 km, the VI of ATF B drops significantly to 165.31, reflecting a notable degradation in its viscosity performance due to usage. When oil treatment is added to this used ATF, resulting in ATF B_1, the VI further decreases to 162.42.

The viscosity stability of the ATFs over temperature changes is visually represented by its graph profiles. While ATF C_0 shows the greatest viscosity reduction, making it less appropriate for demanding, high-temperature applications, ATF B_0 has the most stable viscosity, ensuring dependable lubrication at both low and high temperatures (L. Tang et al., 2015). The behaviour of ATF A_0 and ATF E_0 is in between, with ATF E_0 outperforming ATF A_0 at higher temperatures. Although ATF D_0 is more stable than ATF A_0, it is slightly less stable than ATF E_0, which could affect how reliable it is at high temperatures. These profiles highlight the importance of selecting the appropriate ATF based on the specific operational temperature range and the need for consistent viscosity performance.

ATF B_0 performs best in terms of viscosity stability, offering reliable protection and lubrication at different temperatures. While ATF C_0 may be less effective in high-temperature environments because of its significant viscosity reduction, ATF E_0 also performs well, particularly in higher temperature conditions. Although ATF A_0 has a respectable viscosity at lower temperatures, its performance in demanding applications may be put at risk at higher temperatures due to its increased susceptibility to breakdown viscosity (Martini et al., 2018c). ATF D_0 is appropriate for applications that are moderately demanding because, despite not achieving the stability of ATF B_0 or E_0, it performs better than ATF A_0 due to its intermediate VI.

A higher VI value indicates better fluid stability and reliability in various temperature conditions, with ATF C_0 performing the best in this regard, followed by ATF B_0, ATF E_0, ATF D_0, and ATF A_0. Selecting the right ATF based on its VI and temperature stability is crucial for ensuring optimal performance and longevity of transmission systems. The introduction of oil treatment to used ATFs may provide various improvements, it tends to result in no significant changes in the viscosity index compared to both fresh and used ATFs without oil treatment. This indicates a trade-off between maintaining optimal viscosity stability and enhancing other fluid properties through oil treatment used. These variations highlight the importance of monitoring viscosity and using oil treatments to enhance the longevity and performance of ATF. The results likely reflect the absence of viscosity improvers in used ATF, preventing it from achieving normal viscosity as fresh ATF. The oil treatment appears to help maintain viscosity characteristics of the ATFs, particularly at higher temperatures, suggesting improved thermal stability while restoration of some of the fluid's original properties.

4.3.3 FT-IR Characterization

FTIR spectra revealed the presence of key functional groups associated with ATF base oils and additives. The FTIR analysis of ATF A_0, B_0, C_0, D_0 and E_0 shown in Figure 4.6 reveals important differences in their molecular structures, functional groups, and additive compositions, which directly influence their performance characteristics.

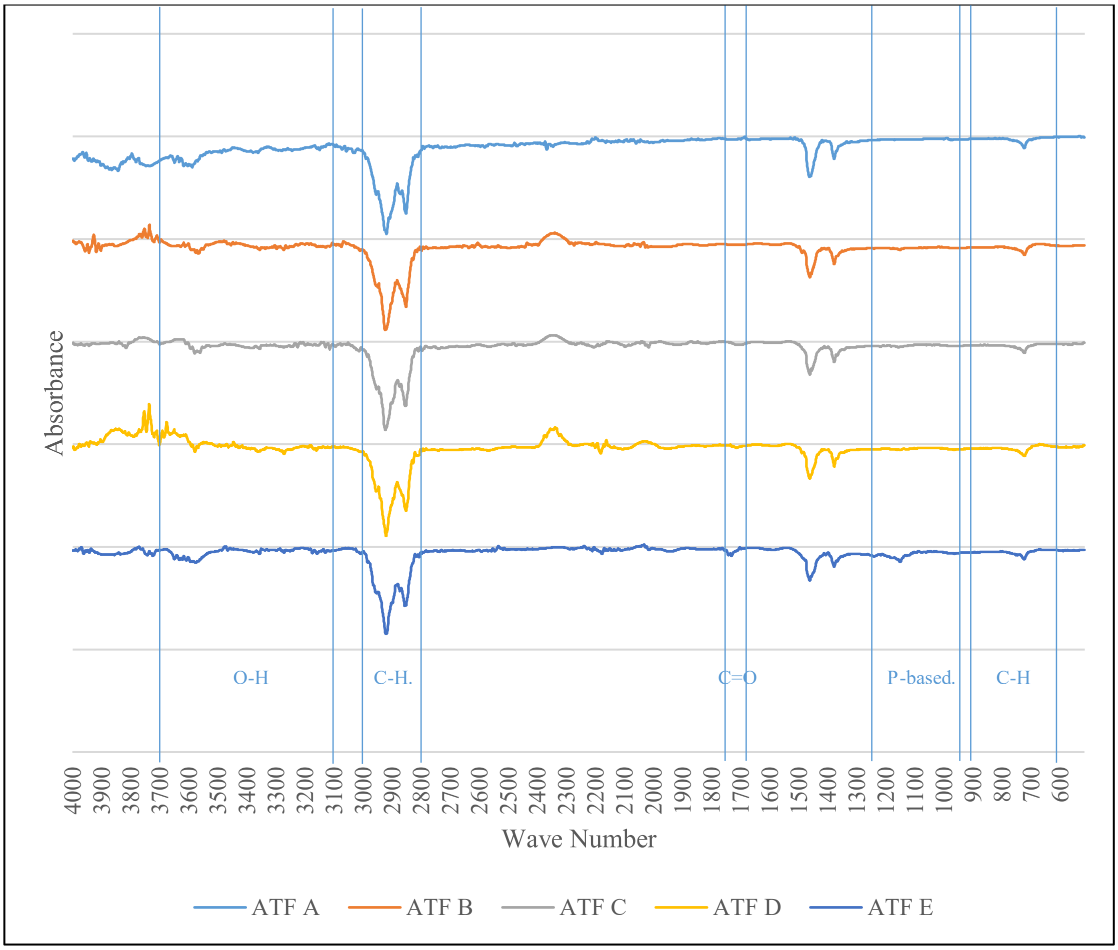


Figure 4.6 FTIR spectra of fresh ATF samples

Within the 3700–3100 cm^{-1} range corresponding to O–H stretching vibrations, ATF C_0 exhibits a stronger absorbance intensity compared to the other samples. This implies a greater concentration of compounds that contain hydroxyl, which may improve thermal resistance and antioxidation (Van De Voort et al., 2011). ATF C_0 may be better suited for high-temperature applications because of these characteristics.

In the 3000–2800 cm^{-1} range, corresponding to C-H stretching vibrations from aliphatic hydrocarbons, all fresh ATF samples show prominent peaks. This suggests that it relies on comparable base oil compositions such as mineral and synthetic hydrocarbon oils (Dominguez-Rosado & Pichtel, 2003). Slight variations in peak intensity, however, are indicative of differences in the hydrocarbons' molecular weight distribution, which can affect the fluids' viscosity-temperature behaviour and overall performance.

In the 1750–1700 cm^{-1} region, corresponding to C=O stretching vibrations of ester compounds, an absorbance is observed in ATF A_0, D_0, and E_0. The strongest peaks among these are found in ATF E_0, showing a higher extension. Because of its enhanced thermal stability and friction modification, ATF E_0 is better suited for high-stress operating environments (De Feo et al., 2015). On the other hand, ATF B_0 is highlighted as having the highest absorbance in the 1250–950 cm^{-1} region, which is linked to phosphorus-based anti-wear additives (Akbari et al., 2016). This indicates a high concentration of phosphorus compounds, which are necessary to protect against high pressure. While ATF C_0 shows weak absorbance, indicating limited anti-wear properties, ATF A_0 and D_0 show moderate levels of these additives.

In the 900–600 cm^{-1} range, which corresponds to C-H bending vibrations of aromatic hydrocarbons, all samples exhibit similar profiles. This shows that the aromatic content of the ATFs is similar, which improves oxidative stability and additive solubility. Despite these parallels, each fluid's unique performance characteristics are revealed by the additive compositions.

The FTIR analysis highlights the unique strengths of each ATF sample. Each ATF sample's distinct advantages are emphasized by the FTIR analysis. Particularly noteworthy is ATF B_0's high concentration of phosphorus-based anti-wear additives, which provide superior oxidative stability and wear protection, making it perfect for demanding applications. ATF E_0 performs exceptionally well in high-stress situations in terms of thermal stability and friction modification due to its high ester content. ATF C_0 is more appropriate for low-stress settings because it has a lower phosphorus content even though it has a strong O-H absorption. ATF A_0 and ATF D_0 are flexible choices for general-purpose use because they offer a well-balanced additive package.

The FTIR analysis of ATF A_0, ATF A and ATF A_1 as shown in Figure 4.7, highlights significant differences in their molecular structures, functional groups, and additive compositions. These differences reflect the impact of usage and treatment on ATF performance characteristics.

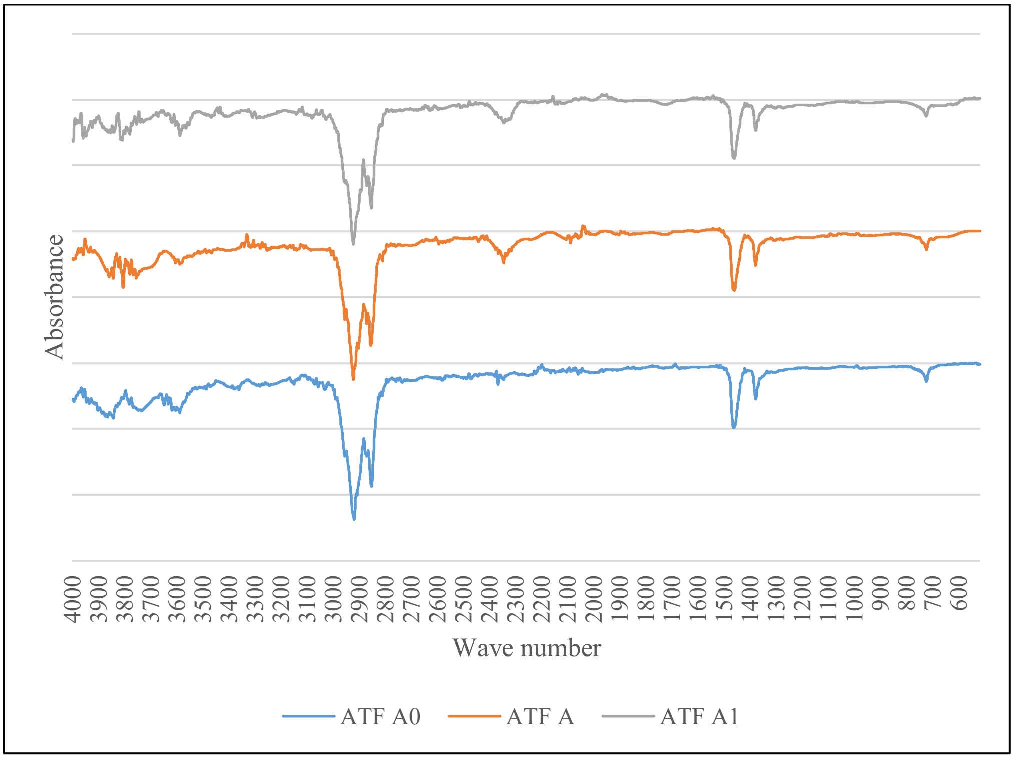


Figure 4.7 FTIR spectra of ATF A_0, A and A_1 samples

In the 3700–3100 cm^{-1} range, which corresponds to O-H stretching vibrations, ATF A_0 exhibits the strongest absorbance compared to the other samples. This implies that hydroxyl-containing compounds, which support antioxidation and thermal resistance, are more 20 prevalent in fresh ATF (Meng et al., 2017). However, after 20,000 kilometres of use, ATF A exhibits a decrease in absorbance in this area, showing the depletion of these protective compounds. ATF A_1 shows a partial recovery of absorbance following treatment, indicating that the transmission oil aids in restoring some of the antioxidative qualities that were lost.

In the 3000–2800 cm^{-1} range, which represents C-H stretching vibrations from aliphatic hydrocarbons, all ATF samples display prominent peaks. This finding indicates that the base oil composition is constant throughout all samples. However, ATF A's peak intensity is marginally lower than ATF A_0's, indicating that hydrocarbons gradually degrade thermally and oxidatively (Campen et al., 2022; Dominguez-Rosado & Pichtel, 2003). The intermediate intensity of the ATF A_1 spectrum suggests that the hydrocarbon structure has been partially restored by the treatment, which could enhance viscosity-temperature stability.

The 1750–1700 cm^{-1} region is associated with C=O stretching vibrations from ester compounds, which play a key role in lubrication and friction modification (Meng et al., 2015; Nasser et al., 2025). In comparison to ATF A_0, ATF A shows a lower absorbance in this area, indicating ester degradation from oxidation and extended use. ATF A_1 exhibits a modest rise in absorbance following treatment, suggesting that the gearbox treatment restores some ester compounds, which could enhance thermal stability and friction properties.

The 1250–950 cm^{-1} range corresponds to phosphorus-based anti-wear additives (Duan et al., 2024; Spikes, 2008). ATF A_0 has the highest absorbance in this region, according to the spectra, indicating that fresh ATF contains a high initial concentration of anti-wear additives. ATF A, however, exhibits a discernible decrease, indicating that these protective additives are progressively consumed over 20,000 kilometres of use. In comparison to ATF A, ATF A_1 shows a moderate increase in absorbance, showing that the gearbox treatment has restored some anti-wear characteristics that could improve protection against additional wear by introducing protection additives such as Zn- and W- elements.

The 900–600 cm^{-1} range corresponds to C-H bending vibrations of aromatic hydrocarbons (Russo et al., 2014). All the samples' spectra display comparable profiles, showing that the aromatic content is unaffected by usage or treatment. To sustain lubricant performance over time, aromatic hydrocarbons help with oxidative stability and additive solubility.

While for ATF B samples, the data is shown in Figure 4.8, which also highlights significant differences in their molecular structures, functional groups, and additive compositions.

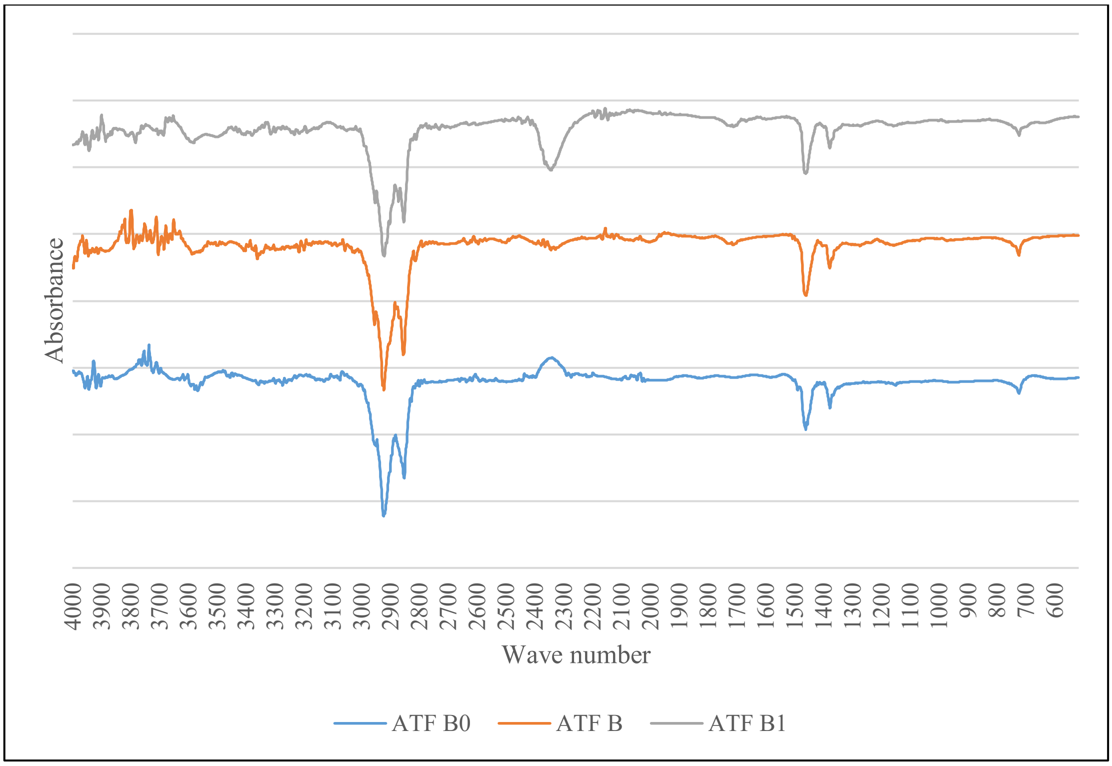


Figure 4.8 FTIR spectra of ATF B_0, B and B_1 samples

In the 3700–3100 cm⁻¹ range, which corresponds to O-H stretching vibrations, ATF B_0 exhibits the strongest absorbance among the samples. It also indicates that hydroxyl-containing compounds, which support antioxidation and thermal resistance, are more prevalent in fresh ATF. ATF B exhibits a discernible decrease in absorbance in this area following 20,000 km of use, suggesting that these protective compounds are being depleted as a result of oxidation and thermal degradation. Following treatment, ATF B_1 shows a modest recovery in absorbance, indicating that the treatment oil helps in restoring some of the antioxidative qualities that were lost.

In the 3000–2800 cm⁻¹ range, corresponding to C-H stretching vibrations from aliphatic hydrocarbons, all ATF B samples exhibit prominent peaks, indicating a consistent base oil formulation that based on mineral or synthetic hydrocarbon oils across them (Dominguez-Rosado & Pichtel, 2003). In contrast to ATF B_0, ATF B exhibits a slight decrease in peak intensity, indicating hydrocarbon degradation following extended use. The intermediate intensity of ATF B_1's spectrum between ATF B_0 and ATF B suggests that the treatment partially restores the hydrocarbon structure, which could enhance viscosity-temperature stability.

The 1750–1700 cm⁻¹ region, associated with C=O stretching vibrations from ester compounds, exhibits notable absorbance in ATF B and ATF B_1. The ester degradation brought on by oxidation and extended use is indicated by the FTIR spectra, which reveal that ATF B has weaker absorbance in this region than ATF B_0. Nevertheless, ATF B_1 shows a modest increase in absorbance following treatment, indicating that the treatment oil partially restores ester compounds, which may improve thermal stability and friction modification (De Feo et al., 2015).

The 1250–950 cm^{-1} region, corresponding to phosphorus-based anti-wear additives, shows the highest absorbance in ATF B_0 (Akbari et al., 2016). This demonstrates that there is an initial high concentration of anti-wear additives in fresh ATF. After 20,000 kilometres of use, ATF B shows a decrease in absorbance, suggesting that these protective additives are progressively exhausted. In comparison to ATF B, the spectrum of ATF B_1 exhibits a higher absorbance, indicating that the treatment oil aids in the restoration of some of the lost anti-wear qualities, potentially improving protection against additional wear.

The 900–600 cm^{-1} range corresponds to C-H bending vibrations of aromatic hydrocarbons. All the samples' FTIR spectra display comparable profiles, indicating that even after extended use and treatment, the aromatic content stays largely constant. To sustain lubricant performance over time, aromatic hydrocarbons are vital for improving oxidative stability and additive solubility.

The effects of treatment oil and usage-induced changes in ATF composition are highlighted by the FTIR analysis. As new ATFs, ATF A_0 and ATF B_0 have a complete concentration of base oil components and necessary additives. Both ATF A and ATF B exhibit degradation from oxidation, heat, and mechanical stress after 20,000 km of use, as evidenced by the depletion of antioxidation, anti-wear, and friction-modifying compounds. ATF A_1 and ATF B_1 show partial restoration of important functional groups after adding treatment oil, indicating that the treatment aids in the recovery of some lost characteristics. These results, however, imply that although the treatment enhances the state of used ATF, it might not completely return it to the performance level of new ATF.

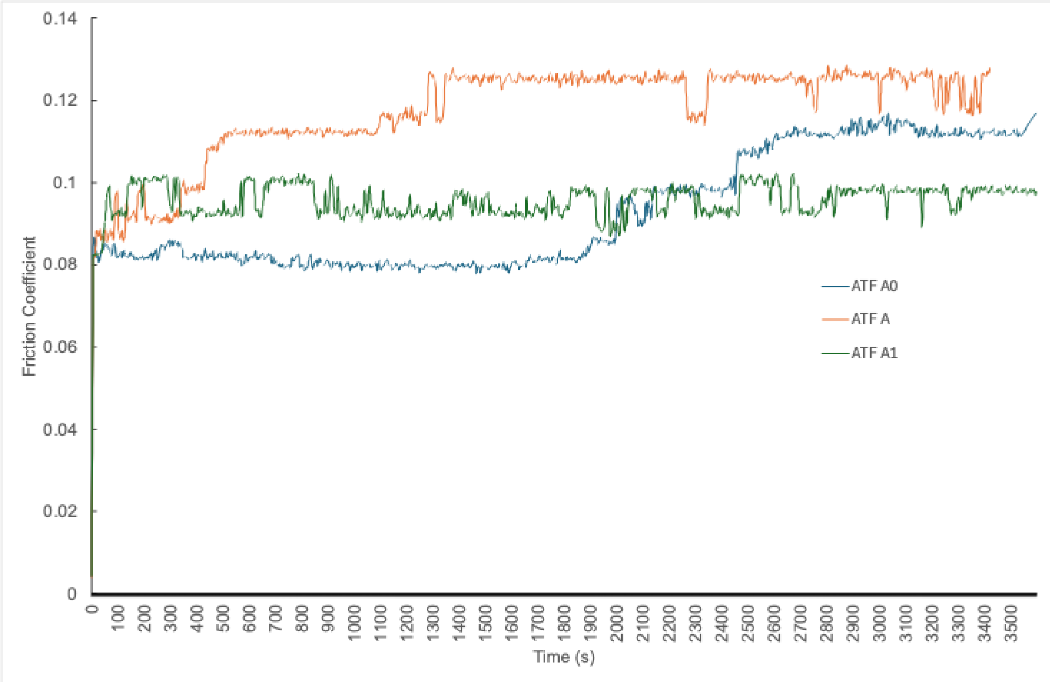
4.4 Tribological Properties of Fresh ATFs, Used ATFs and Treated ATFs

The four-ball tests were performed to assess the wear preventive and extreme pressure characteristics of the fresh, degraded and treated ATFs.

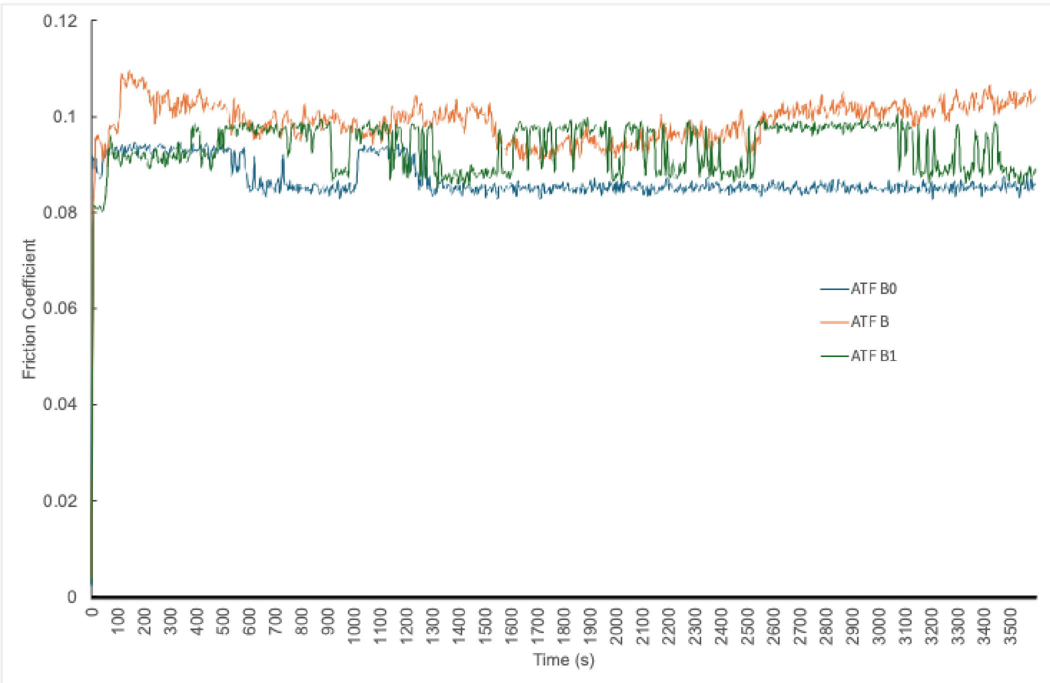
4.4.1 Wear Preventive (WP) Measurement

4.4.1.1 Coefficient of Friction

The wear preventive characteristic, or the lubricating ability, and the effectiveness of the ATF samples are shown in Figure 4.9 for the ATF A and ATF B respectively. The friction coefficient trends over time are compared between the fresh, used, and treated ATF samples.



(a)

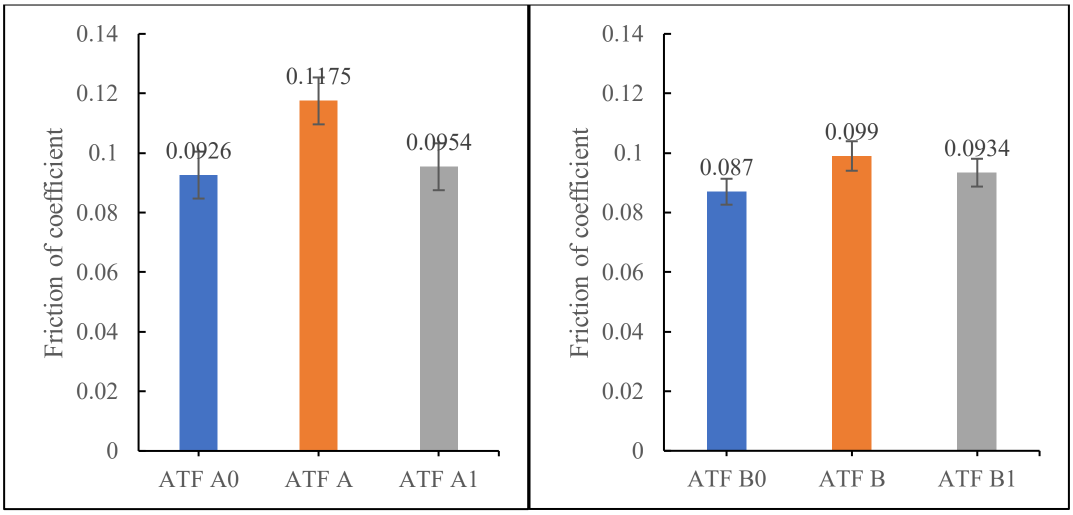


(b)

Figure 4.9 The friction coefficient over time of (a) ATF A and (b) ATF B

Both treated ATF (ATF A_1 and B_1) show a more stable graph line as compared to others. While new and used ATFs (ATF A_0, ATF A, ATF B_0 and ATF B) show a slightly unstable and inclined pattern at some point.

Across the running period, the average values of the friction coefficient were obtained and measured as shown in Figure 4.10. From the graph, treated ATF A_1 and B_1 achieved the lower average coefficient (CoF) of 0.0954 and 0.0934, respectively. Both treated ATF were unable to reach the initial result as fresh ATF. Figure 4.10 shows the friction coefficient of (a) ATF A and (b) ATF B.



(a) (b)

Figure 4.10 The friction coefficient of (a) ATF A and (b) ATF B

Based on the results, both treated ATF A_1 and B_1 show better coefficients of friction (CoF) compared to used ATF A and B. While ATF B_1 improved by 5.66%, ATF A_1 improved by 18.81%. All measurements were conducted in triplicate under identical test parameters (300 g load, 60 CPM, 10 mm/s), and the standard deviation of CoF values was below 3% for all samples, indicating good repeatability and measurement stability. The inclusion of elements like zinc and phosphorous in the oil treatment, which function as anti-wear and extreme pressure additives, may contribute to this improvement. These additives, also referred to as friction modifier additives, are widely added as nanoparticles to lubricating oils and have a proven track record of lowering wear and friction (Chen, 2010; Shahnazar et al., 2016). Another study by (W. Wang et al., 2018a) has proven that the phosphorus elements in as additives exhibit strong super lubricity in an aqueous solution, maintaining very low resistance to shear across different additive concentrations, contact pressures, and sliding velocities. This implies that the enhanced friction and wear properties seen in ATF A_1 and B_1 are largely due to the addition of these additives to the oil treatment. These findings demonstrate the efficacy of the oil treatment in improving the wear preventive measures of the ATFs, even though the treated ATFs do not entirely return the CoF to the level of fresh ATFs.

The reduction in CoF is primarily driven by anti-wear and extreme pressure additives, such as Zn and P, which form a protective tribo-film on contact surfaces during sliding (Alias et al., 2018). This film reduces direct contact, stabilizes shear behaviour, and lowers friction. Oil treatment also modifies the viscosity of used ATF, increasing film thickness and enhancing load-carrying capacity. Stable tribo-film formation and improved lubrication film strength lead to the enhanced friction performance observed in ATF A_1 and B_1.

The four-ball tribo-test provides controlled and standardized contact conditions for comparative analysis, it represents a simplified sliding contact that does not fully replicate the complex hydrodynamic, thermal, and shear conditions present in actual automatic transmission systems. The test operates under constant load and speed without dynamic gear engagement or fluid circulation effects. Therefore, the results primarily reflect boundary and mixed lubrication behaviour rather than full-system transmission performance.

These findings demonstrate the efficacy of the oil treatment in improving wear-preventive characteristics of the ATFs, even though the treated ATFs do not entirely return the CoF to the level of fresh ATFs. The sustainability of this improvement depends on tribo-film durability and additive activity retention during prolonged operation. The partial restoration rather than full recovery is attributed to irreversible physicochemical degradation of the used ATF. Base oil oxidation produces acidic species and sludge that permanently alter molecular structure and polarity. These changes cannot be reversed by post-treatment additives. In addition, depletion and chemical transformation of the original additive package disrupt synergistic interactions originally designed into the fresh formulation. Newly introduced additives must function within a chemically aged base oil matrix, where altered surface energy, residual oxidation products, and competitive adsorption phenomena restrict optimal tribo-film growth. The oxidation by-products may interfere with additive activation reactions, reducing their surface reactivity and limiting tribo-film thickness and uniformity. While the treatment effectively enhances boundary lubrication and viscosity modification, it cannot fully reconstruct the original base oil chemistry and additive synergy present in fresh ATF, which explains the incomplete recovery of friction performance.

4.4.1.2 Wear Scar Analysis

The wear scar under microscope for the tested ATF samples were illustrated in the Figure 4.11and Figure 4.12 for the ATF A and ATF B samples respectively.

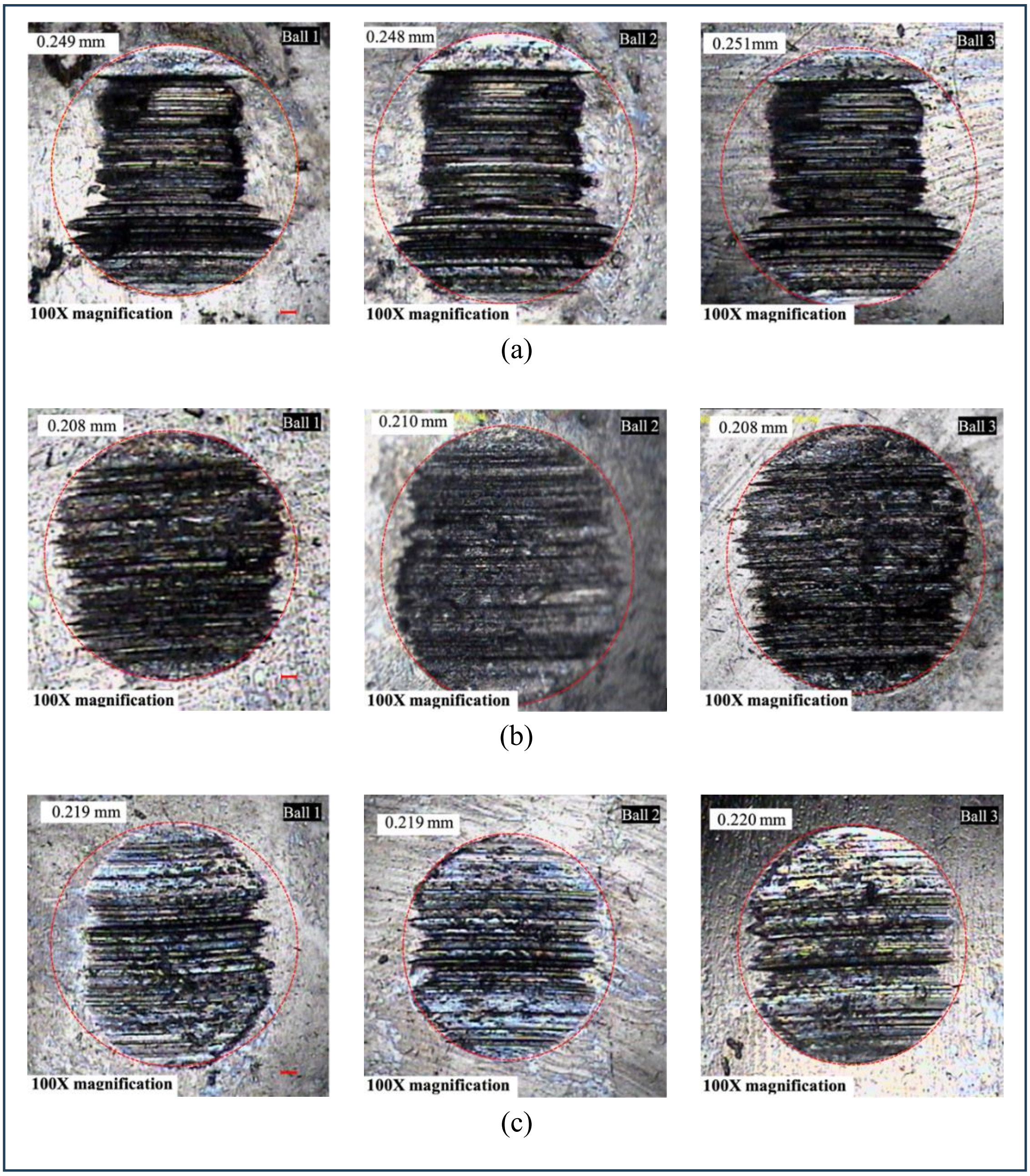


Figure 4.11 Wear scar of 3 balls of (a) ATF A_0, (b) ATF A and (c) ATF A_1

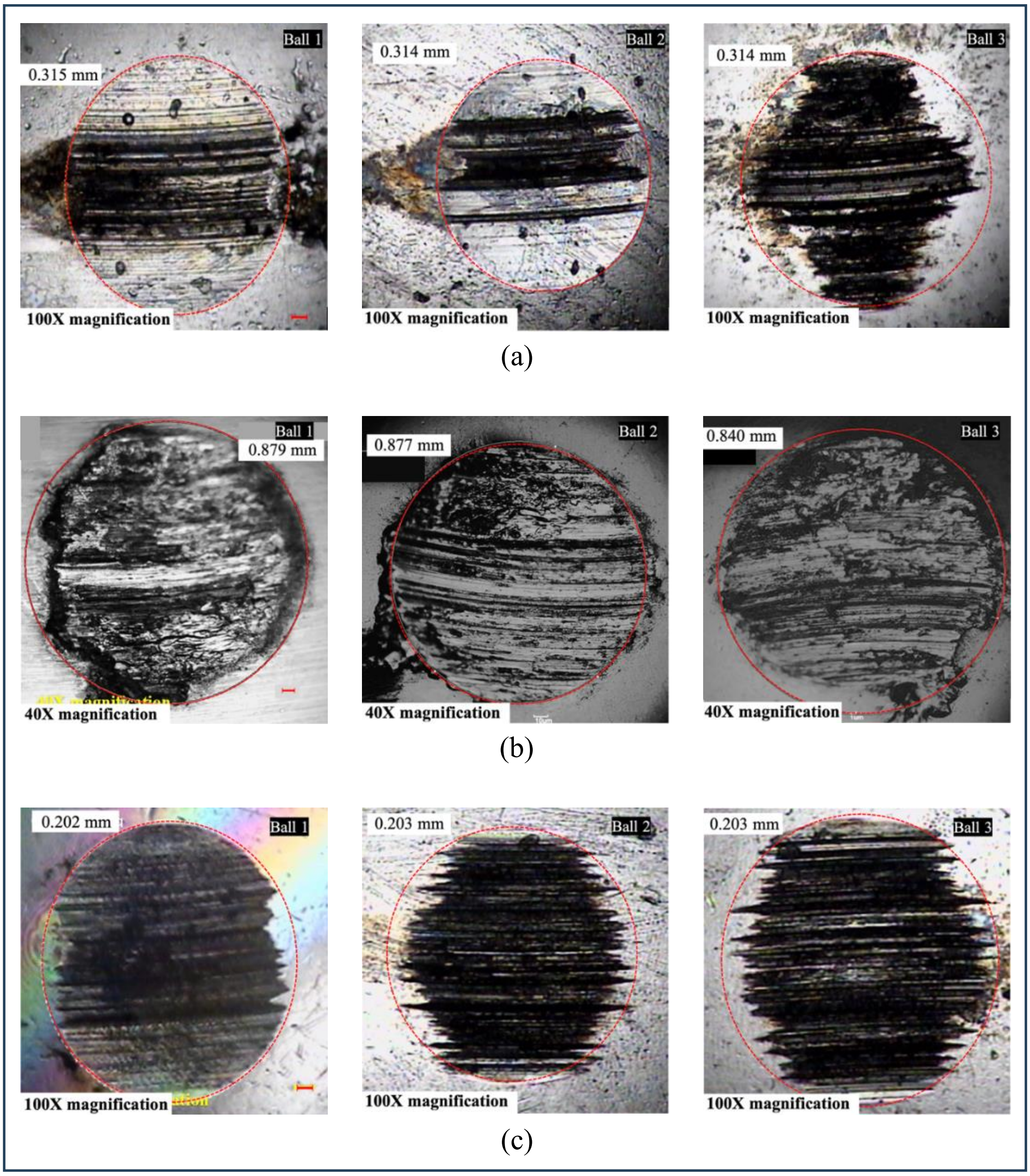


Figure 4.12 Wear scar of 3 balls of (a) ATF B_0, (b) ATF B and (c) ATF B_1

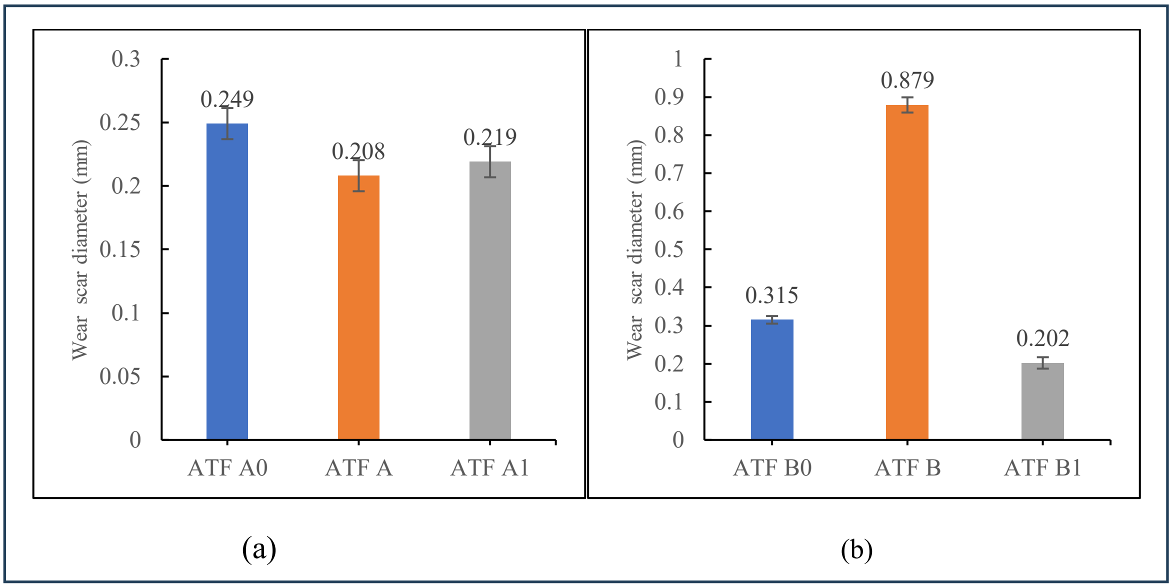


Figure 4.13 presents the average wear scar diameters for ATF samples A and B.

For ATF A, the wear scar diameters of the fresh (ATF A_0), used (ATF A), and treated (ATF A_1) samples were 0.249 mm, 0.208 mm, and 0.219 mm, respectively. In comparison, the corresponding values for ATF B_0, ATF B, and ATF B_1 were 0.315 mm, 0.879 mm, and 0.202 mm, respectively.

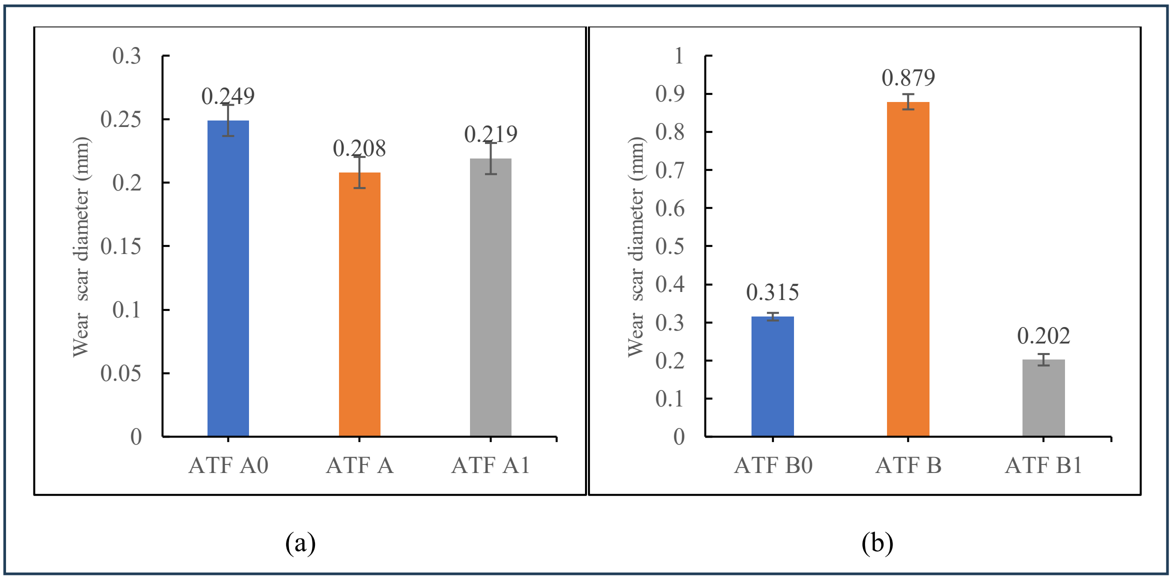


Figure 4.13 Average wear scar diameter of (a) ATF A and (b) ATF B

The wear scar analysis of ATFs reveals significant changes in wear protection with the application of oil treatment. ATF A_0 has a wear scar diameter of 0.249 mm, and after 20,000 kilometres of use, it drops to 0.208 mm. In contrast, applying oil treatment to the used ATF A causes a marginally larger wear scar diameter of 0.219 mm, which is a change of roughly 5.29% in percentage. The oil treatment did not completely restore the degraded fluid's wear resistance.

ATF B exhibits significant deterioration, with a wear scar diameter that begins at 0.315 mm and increases to 0.879 mm after 20,000km mileage. In comparison to used ATF B, oil treatment in ATF B significantly reduces the wear scar diameter to 0.202 mm, indicating a percentage improvement of roughly 76.96%. This result aligns with findings from other studies, which show that adding additives to automotive lubricants can reduce wear scar diameter by more than 9% (Szabó et al., 2023; Thachnatharen et al., 2022), thus validating the effectiveness of the treatment. These findings underscore the critical role of oil treatment in mitigating wear and preserving ATF performance, demonstrating their efficacy in enhancing lubrication and protective capabilities under demanding operating conditions.

The wear surface analysis shows that oil treatment of ATFs can result in better wear scars, suggesting enhanced wear protection. The elements P and Zn that acts as anti-wear elements may be the contributor to the reduce in the wear scar. Previous research has demonstrated the usefulness of those components as lubricant additives for the reduction of friction and wear (Barton & Karathanasis, 2002). According to Stachowiak and Batchelor's (2006), synthetic lubricants contain compounds with phosphides and sulphide ions that have a propensity to react with the steel ball surfaces, preventing metallic contact to some extent and reducing wear. Additives containing metals like Zn and Fe may contribute to the production of tribo-films on worn surfaces, claim Zhao's. in their study (Zhao et al., 2014). This highlights the crucial applying oil treatments to improve ATF's durability and wear resistance to gradually improve gearbox component protection.

4.4.2 Extreme Pressure (EP) Measurement

The EP properties of the degraded and treated ATFs are depicted in Table 4.3, which presents the weld loads. Since there were no discernible differences in the load-carrying capacity between the treated and degraded ATFs, the results demonstrate that the treatment process successfully restored or preserved the critical extreme pressure (EP) performance required for reliable lubrication under high-stress conditions.

Table 4.3
The ATFs extreme properties

Samples	Weld load (kgf)
ATF A_0	240 ~ 245
ATF A	250 ~ 260
ATF A_1	170 ~ 180
ATF B_0	140 ~ 150
ATF B	120 ~ 130
ATF B_1	400 ~ 410

The baseline performance for both series was established using the fresh oils ATF A_0 and ATF B_0. ATF A_0 exhibited a weld load of 240~245 kgf, which was substantially higher than ATF B0 at 140~150 kgf. This indicates that the ATF A series fluid possessed a stronger inherent extreme pressure capability and offered better resistance to mechanical stress in its fresh state (H. Li et al., 2022; Y. Li, Zhang, et al., 2019). This shows the effectiveness of extreme pressure and anti-wear additives present in treatment oil.

After 20 000 km of service, the degraded oils showed different behavioural trends. ATF A demonstrated a slight improvement to 250~260 kgf, suggesting that degradation may have induced tribo-chemical reactions such as the development of protective boundary films that marginally increased its load bearing capacity (Di et al., 2020b; Xu et al., 2025; Yadav et al., 2018). In contrast, ATF B deteriorated to 120~130 kgf, reflecting additive depletion, oxidation, and reduced film integrity, which weakened its extreme pressure performance compared to the fresh fluid (Farfan-Cabrera et al., 2021b).

For treated oils, ATF B_1 shows a substantial enhancement, achieving 400~410 kg, which surpassed both its fresh and degraded oils by a wide margin. This improvement indicates that the treatment oil effectively replenished or strengthened the extreme pressure additive system, promoting the formation of a more robust protective tribo-film under high loads (Di et al., 2020b). ATF A_1 exhibited a weld load of 170~180 kgf, lower than both ATF A_0 and ATF A. This reduction likely due to additive incompatibility or dilution of existing extreme pressure components, which reduced its protection capability (García Tuero et al., 2022).

These findings demonstrate that degradation and additive treatment influence the extreme pressure performance of ATF differently across formulations. While treatment significantly enhanced ATF B_1, it weakened ATF A_1, highlighting that treatment effectiveness is strongly dependent on additive and fluid compatibility. Further analysis of the chemical interactions and tribo-film composition is essential to optimise treatment strategies and ensure reliable performance across different ATF systems.

4.5 Concluding Remarks

In this chapter, the results of the treatment oil samples has been presented. The ATFs include both fresh and used fluids, with the latter undergoing treatment using advanced additives to enhance their properties. The blending process incorporated treatment oils and utilized methods such as ultrasonication to achieve uniform dispersion and improved performance. A detailed analysis of the ATF properties, including viscosity, anti-wear performance and friction characteristics, has been presented. These results were compared with reference data from commercially available ATFs to validate the findings. The verified data represent a significant contribution to the knowledge base and the automotive industry, particularly in advancing the development of high-performance ATFs.

CHAPTER 5
CONCLUSION

5.1 Conclusion

This study aims to characterise the physicochemical properties of commercial ATFs and treatment oil, assess the effectiveness of treatment oil in improving the quality of used ATFs, and evaluate the tribological performance of the treated fluids. A 4 vol.% concentration of treatment oil was blended into used ATF via ultrasonication and mechanical stirring to ensure uniform dispersion. The physicochemical and tribological properties of the treated ATF were then compared with both fresh and used ATF to assess impact on friction, wear, and lubrication performance. Significant improvements were observed in the treated ATF, validating the treatment oil's effectiveness in enhancing fluid functionality. Based on the findings, the research objectives were achieved as follows:

a. The physicochemical properties of fresh ATFs and the treatment oil were characterized using viscosity measurements, elemental analysis, and FTIR spectroscopy. These analyses revealed distinct additive profiles and molecular structures, confirming the chemical baseline and functional integrity of each fresh ATF formulations.

b. Analysis between fresh, used, and treated ATFs showed that the used ATF exhibited significant degradation, including a reduced viscosity index and depletion of anti-wear and antioxidant elements. However, after blending with 4% treatment oil, the treated ATF showed partial restoration of its chemical properties, with characteristics approaching those of fresh ATF. Elemental and FTIR data confirmed the reintroduction of key additives and functional groups, while viscosity stabilization indicated improved fluid integrity and potential enhancement of performance.

c. Tribological evaluation showed that the treatment oil effectively enhanced the frictional and anti-wear performance of used ATFs. The treated samples (A_1 and B_1) recorded lower friction coefficients of 0.0954 and 0.0934, showing reductions of 18.81% and 5.66% compared to used ATFs. Wear analysis revealed a substantial improvement, with ATF B_1 exhibiting a 76.96% reduction in wear scar diameter (from 0.879 mm to 0.202 mm). The presence of phosphorus and zinc additives likely promoted tribo-film formation, improving surface protection. ATF B_1 also achieved the highest weld load of 400–410 kgf, confirming enhanced load-carrying capacity. These results provide clear quantitative evidence that the treatment oil enhances friction reduction and anti-wear performance of degraded ATFs, although full restoration to fresh ATF performance was not achieved.

The findings validate the treatment oil's potential in partially restoring degraded ATF performance, particularly in terms of friction and wear characteristics. While the treatment oil improves physicochemical and tribological properties, it represents a short-term solution rather than a complete replacement strategy. Future studies should investigate durability under long-term operating conditions and evaluate compatibility with various ATF formulations and transmission types to confirm broader applicability.

5.2 Recommendations

This research represents a significant step toward sustainable lubricant development. However, further studies are recommended to refine and expand the applications of treated ATF:

i. Improving the additive formulation by looking into the use of advanced additives, like extreme-pressure additives and nano-additives, to further increase thermal stability, load-carrying capacity, and wear resistance. Antioxidants and corrosion inhibitors can also stop oxidative deterioration and increase the shelf life of treated ATF.

ii. To ensure adherence to environmental regulations, conduct more thorough testing by expanding the scope of the study to include biodegradability, environmental impact assessments, and long-term thermal and oxidative stability.

iii. To improve dependability in real-world situations, test the treated ATF's compatibility with automotive parts like gaskets, seals, and metal surfaces to make sure it doesn't corrode or degrade.

iv. Verify the performance of the treated ATF in field tests conducted in real-world scenarios, such as long-duration, high-temperature, and high-pressure testing. Examine the treated ATF's capacity to sustain viscosity and stability over time in demanding applications, as well as its ability to prevent wear and retain film.

These recommendations will support the continued development of ATF and treatment oil, ensuring its effectiveness, sustainability, and compatibility with industrial and automotive requirements.

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Muhamad Aidil Tasnim Roslan graduated with a Bachelor of Engineering (Hons) in Mechanical Engineering from Universiti Teknologi MARA, Shah Alam, in 2021. His undergraduate thesis explored the mechanics of bicruciate-retaining Total Knee Arthroplasty (BCR-TKA), with an emphasis on its relationship to the posterior tibial slope, reflecting his strong interest in biomechanics. Currently, he is pursuing a Master of Science in Mechanical Engineering at Universiti Teknologi MARA, where his research focuses on the tribological effects of treatment oil in automotive transmission fluid (ATF). This work aims to enhance the performance, wear resistance, and sustainability of transmission systems, reflecting his dedication to advancing automotive engineering solutions.

LIST OF PUBLICATION

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