แหล่งหินบะซอลต์ของจังหวัดลพบุรี : วัตถุดิบที่มีศักยภาพสำหรับการผลิตใยบะซอลต์

นายเสียงเหล็ง เฮือน

วิทยานิพนธ์นี้เป็นส่วนหนึ่งของการศึกษาตามหลักสูตรปริญญาวิศวกรรมศาสตรมหาบัณฑิต
สาขาวิชาวิศวกรรมทรัพยากรธรณี ภาควิชาวิศวกรรมเหมืองแร่และปิโตรเลียม
คณะวิศวกรรมศาสตร์ จุฬาลงกรณ์มหาวิทยาลัย
ปีการศึกษา 2558

BASALT RESOURCES IN LOPBURI PROVINCE:

A POTENTIAL RAW MATERIAL FOR BASALT FIBER PRODUCTION

Mr. Seangleng Hoeun

A Thesis Submitted in Partial Fulfillment of the Requirements

for the Degree of Master of Engineering Program in Georesources Engineering

Department of Mining and Petroleum Engineering

Faculty of Engineering

Chulalongkorn University

Academic Year 2015

Thesis Title	BASALT RESOURCES IN LOPBURI PROVINCE: A POTENTIAL RAW MATERIAL FOR BASALT FIBER PRODUCTION
By	Mr. Seangleng Hoeun
Field of Study	Georesources Engineering
Thesis Advisor	Pipat Laowattanabandit, Ph.D.

Accepted by the Faculty of Engineering, Chulalongkorn University in Partial Fulfillment of the Requirements for the Master's Degree

....Dean of the Faculty of Engineering

(Associate ProfessorSupot Teachavorasinskun, D.Eng.)

THESIS COMMITTEE

....Chairman

(Associate Professor Dawan Wiwattanadate, Ph.D.)

....Thesis Advisor

(Pipat Laowattanabandit, Ph.D.)

....Examiner

(Apirat Theerapapvisetpong, Ph.D.)

....External Examiner

(Associate Professor Pornkasem Jongpradist, Ph.D.)

เสียงเหล็ง เฮือน : แหล่งหินบะซอลต์ของจังหวัดลพบุรี : วัตถุดิบที่มีศักยภาพสำหรับการผลิตใยบะซอลต์ (BASALT RESOURCES IN LOPBURI PROVINCE: A POTENTIAL RAW MATERIAL FOR BASALT FIBER PRODUCTION) อ.ที่ปรึกษาวิทยานิพนธ์หลัก: พิพัฒน์ เหล่าวัฒนบัณฑิต, 73 หน้า.

นอกจากเป็นหินที่ให้ทับทิมและไพลิน หินบะซอลต์และหินกลุ่มบะซอลต์สามารถนำมาใช้ประโยชน์ ด้านอื่นๆ โดยเฉพาะในการผลิตหินก่อสร้างและทำเส้นใยบะซอลต์ หินบะซอลต์ถูกนำมาใช้เป็นมวลรวมในงานคอนกรีต มวลรวมในการทำถนน ใช้เป็นหินรางรถไฟ และใช้เป็นหินประดับ นอกจากประโยชน์ปกติดังกล่าว ใยหินคุณภาพสูงสามารถดึงได้จากการหลอมหินบะซอลต์ ที่ให้คุณสมบัติที่ดีทั้งทางด้านกลศาสตร์และเคมี เทียบกับใยจากแร่ใยหินที่อันตราย นอกจากความแข็งแรงที่สูงกว่าและทนทานในด่างได้ดีกว่า E-glass ใยบะซอลต์ยังถูกกว่าใยคาร์บอนที่เบาและแกร่ง ด้วยความทนทานต่อความร้อนและการขัดสี ใยบะซอลต์จึงสามารถทดแทนแร่ใยหินในการใช้ประโยน์หลายอย่าง แม้ว่าหินบะซอลต์ทั้งหมดสามารถนำมาผลิตใยบะซอลต์ได้ แต่คุณภาพผลิตภัณฑ์ขึ้นอยู่กับองค์ประกอบทางแร่ องค์ประกอบทางเคมีและพฤติกรรมการตกผลึกจากของการหลอมบะซอลต์

จุดมุ่งหมายของงานวิจัยนี้เพื่อประเมินความเหมาะสมของทรัพยากรบะซอลต์ในจังหวัดลพบุรีเพื่อผลิตใยบะซอลต์ ผลลัพท์จากการบูรณาการผลการวิเคราะห์ทางศิลาวิทยา การสำรวจทางแร่วิทยาและทางธรณีเคมี รวมถึงคุณลักษณะของของเหลวจากการหลอมบะซอลต์ถูกนำเสนอในการวิจัยนี้เพื่อนำมาใช้ในการประเมินความเหมาะสมของทรัพยากรบะซอลต์สำหรับการผลิตเส้นใย ความซับซ้อนของวิวัฒนาการทางธรณีวิทยาของภาคกลางประเทศไทยทำให้เกิดการแปรปรวนค่อนข้างมากขององค์ประกอบและการกำเนิดของบะซอลต์ ในบางพื้นที่หินบะซอลต์มีการเปลี่ยนสภาพค่อนข้างมากทั้งนี้เนื่องจากการไหลของหินหนืดบนชั้นหินไรโอไรต์ที่มีอยู่ก่อนแล้ว ซึ่งทำให้เกิดการผุพังได้ง่าย ในขณะที่บางบริเวณหินบะซอลต์ถูกแปรสภาพทำให้เกิดการเปลี่ยนองค์ประกอบทางแร่และทางเคมี อย่างไรก็ตามหินบะซอลต์สดถึงหินบะซอลต์เนื้อแอนดีซิติกถูกพบในบางพื้นที่ ซึ่งเหมาะสมสำหรับใช้ในการผลิตเส้นใยเพราะไม่มีการเปลี่ยนองค์ประกอบทางแร่และทางเคมี หินบะซอลต์ครอบคลุมพื้นที่ประมาณ 1 ใน 4 ของจังหวัดลพบุรี ซึ่งตั้งอยู่ใกล้อุตสหกรรมหลายแห่งซึ่งเป็นประโยชน์ในการตั้งโรงงานผลิตใยบะซอลต์

ภาควิชา	วิศวกรรมเหมืองแร่และปิโตรเลียม	ลายมือชื่อนิสิต	....
สาขาวิชา	วิศวกรรมทรัพยากรธรณี	ลายมือชื่อ อ.ที่ปรึกษาหลัก	....
ปีการศึกษา	2558		

5770495521 : MAJOR GEORESOURCES ENGINEERING
KEYWORDS: ASBESTOS / BASALT FIBER / LOPBURI BASALT / ROCKWOOL

SEANGLENG HOEUN: BASALT RESOURCES IN LOPBURI PROVINCE: A POTENTIAL RAW MATERIAL FOR BASALT FIBER PRODUCTION. ADVISOR: PIPAT LAOWATTANABANDIT, Ph.D., 73 pp.

Apart from a good host of ruby and sapphire, basalts and basaltic rocks can be used for other purposes, especially as producing construction material and making basalt fibers. Basalt has been widely used as concrete aggregate, pavement aggregate, railroad ballast and dimension stone. Not only these conventional applications, but also high quality fiber can be drawn from molten basalt with outstanding mechanical and chemical advantages comparing to hazardous asbestos fiber. Having higher strength and more stable in alkalinity than E-glass, basalt fiber is cheaper than the high-strength-low-density carbon fiber. With high thermal and abrasion resistance, basalt fiber could replace asbestos in various usages. Although all basalt can be used to make fiber, its quality depends largely on mineralogy, chemical composition and recrystallization behaviors of basaltic melts.

The aim of this research is to evaluate the suitability of basalt resources in Lopburi Province, Thailand for making basalt fiber. Integrated results of petrological analysis, mineralogical and geochemical investigation as well as basalt melts' characterization are presented in this research to delineate the suitability of the basalt resources for producing fiber. The complex geological evolution in central Thailand introduced very high variations of basalt composition and genesis. In some occurrences, basalt found highly altered due to the flow of basaltic lava over pre-existing rhyolitic layer, making it more sensitive to weathering. Meanwhile, some basalt deposits might be metamorphosed through which it makes changes in mineral and chemical compositions. However, fresh basalt to andesitic basalt was also found in some areas, which might be suitable for making fiber due to its unchanged mineralogical and chemical composition. Covering approximately one fourth of the total area of the province, Lopburi basaltic rocks are situated fairly close to a number of industrial zones, where are very advantageous for basalt fiber production.

Department:	Mining and Petroleum Engineering	Student's Signature	....
Field of Study:	Georesources Engineering	Advisor's Signature	....
Academic Year:	2015		

ACKNOWLEDGEMENTS

Firstly, I would like to offer my special thanks to Dr. Pipat Laowattanabandit, my thesis advisor, for his strong support and encouragement. His willingness to give his time so generously has been very much appreciated. This work could not be completely accomplished with his continuous motivation, help and advising.

My grateful thanks also extended to ASEAN-Scholarship Program of Graduate School of Chulalongkorn University for providing me this incalculable chance to take master's degree here and financially support me. Without this support I would not be able to gather such valuable knowledge for personal and social benefits.

I greatly thank to all professors and stuffs of Department of Mining and Petroleum Engineering, Chulalongkorn University for priceless knowledge, patient guidance, enthusiastic support and encouragement. I have been warmly welcomed, motivated, and facilitated during my life as international student here. I would also like to convey my gratitude to all my thesis committee for useful critiques and recommendation for this research.

Special thanks should be given to geological survey team of Department of Mineral Resources of Thailand for arranging fieldwork, accommodating warmly and providing many inevitable data for this research. Without their kind supports, it would be very hard for me to gather those necessary data.

I would love to express my great appreciate to all friends and classmates for sharing fun, motivation, supports. It's such unforgettable memory to have been pass through such bitter and wonderful moments together during the master student life.

Last but not least, I wish to thank my parents as well as my siblings for their powerful love, compassion and encouragements.

CONTENTS

Page

Page

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1: INTRODUCTION

1.1. Background

Composite materials become materials of choices in advance engineering applications, crediting to its high and desirable quality comparing to conventional materials. For specific application, two or more materials with different physical and chemical properties have been composited to produce new materials which have unique characteristics, significantly distinct from its individual components. Fibers are widely acknowledged to be inevitable material using in composites for achieving either one or more of the following characteristics: high strength to weight ratio, insulation capability, corrosive and fire resistance, firm and stiffness, and greater friction [1].

Although basalt fibers have a similar composition comparing to glass fiber, it has better mechanical properties, higher resistivity to heat, alkalinity, acidity and salinity. These outstanding characteristics make basalt fiber to be a good material for reinforcing concrete, polymer and steel etc. Relatively a newcomer in fiber reinforced polymers (FRPs) and structural composites, basalt fiber has better abrasion property comparing to asbestos. Basalt required no additives and consumed less energy to make fiber, resulting in cheaper and more reliable than glass and carbon fiber. Natural basalt rock, the only raw material for basalt fiber production, is melted at 1450-1500 ^{o}C in furnace. The molten basalt is passed through a continuous spinning process where a platinum/rhodium crumble brush basalt to create great reinforcement materials in form of chopped or continuous fibers, which can be potentially used in textile and composite field [2].

Quality and type of raw material, manufacturing process and characteristics of the final product determine the base cost of basalt fibers. Not so difference for the base cost, the mechanical, physical and chemical characteristics of fiber is depended on raw material quality and composition. In other words, the composition of raw material will determine degree of strength, thermal stability, resistivity to chemical in the fibers [3].

1.2. Problem Statements

Having outstanding properties in terms of strength, thermal and chemical resistance and other advantages over other fibers being in use at present, basalt fiber has earned a lot of attention from researchers [4]. The wide availability of basaltic rock reflects its potential to be cheap, reliable and sustainable alternative of fibrous materials in future. Glass fiber required varieties of raw materials to produce fibers at the same or lower quality comparing to basalt fiber and the limited resources brought the questions over its price and sustainability. Carbon fiber, which could provide highest strength to weight ratio, is irreplaceable by basalt, yet chemical and thermal resistivity of basalt fiber is unbeatable by carbon fiber, one of the most expensive fiber. Although has been flagged as hazardous material, asbestos is still cheap and remains being used in construction materials and braking plates in less developed countries. Recent researches showed that basalt fiber could be produced at comparable cost to asbestos and it performs much better than asbestos in construction composites, fire prevention and abrasion plates.

At the meantime, in Thailand as well as in industrializing countries, utilization of glass fiber and asbestos in polymer composites, construction materials and abrasion equipment remain popular, while basalt resources are largely available almost everywhere across the countries. This raise question over the research topic to study potential of basalt in Thailand to produce basalt fiber.

1.3. Objective

This research is conducted to evaluate the potential and suitability of making basalt fiber from basalt resources in Lopburi Province, Thailand.

1.4. Scope of works

Among basalt resources in Thailand, Lopburi basalt has been selected for studying in this research due to the following reasons:

- Lopburi basalt is located fairly close to numerous Thailand’s industrial zones, giving chance to manufacturing fiber near demand.

- Lopburi basalt is documented as non-gem-related basalt, which is more likely to be suitable for making basalt fiber.
- Limitations and accessibilities are also the crucial factor behind the decision to select Lopburi as study area. Generally, Lopburi is highly accessible and there is a potential to develop a basalt mine.

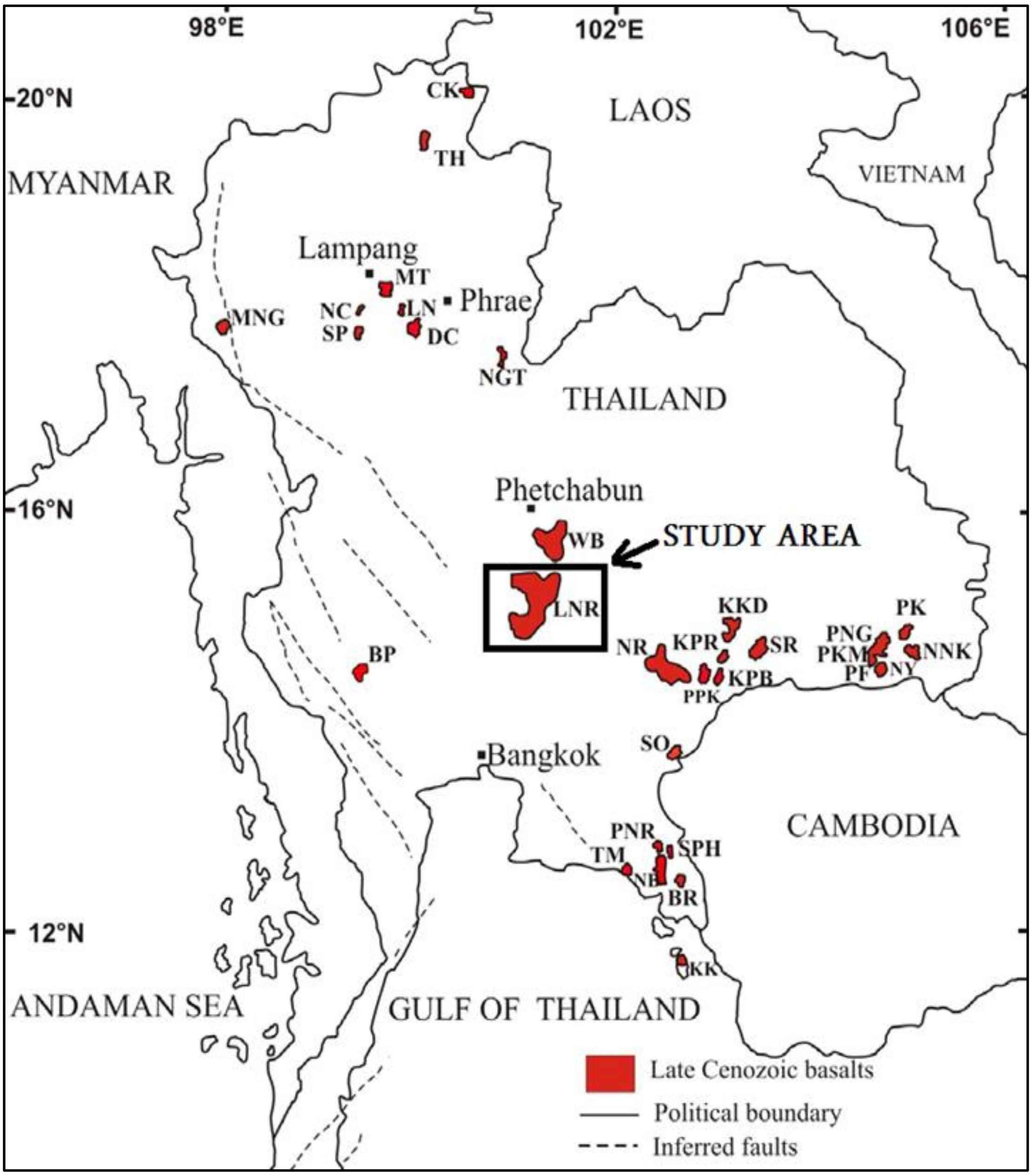


Figure 1-1: Map showing Cenozoic Basalt in Thailand and the study area

CHAPTER 2: LITERATURE REVIEWS

2.1. Reviews on basalt fiber

2.1.1. Basaltic Rocks

As mafic extrusive igneous rock, basalt commonly have aphanitic texture and known to be composed of primary minerals such as plagioclase (cal-feldspar) and pyroxene as well as olivine as minor minerals (see Figure 2-1). Basalt is originated form frozen mafic magma in various geologic environment, ranging from continental to oceanic environment. Pyroxene and plagioclase, which are silicate minerals represent 80% of mineral composition of basalt, resulting in moderately high SiO_2 content, while Al_2O_3 is the second abundance oxide, following by Fe_2O_3, CaO, MgO, Na_2O, K_2O and trace of TiO_2, MnO, P_2O_5 and Cr_2O_3.

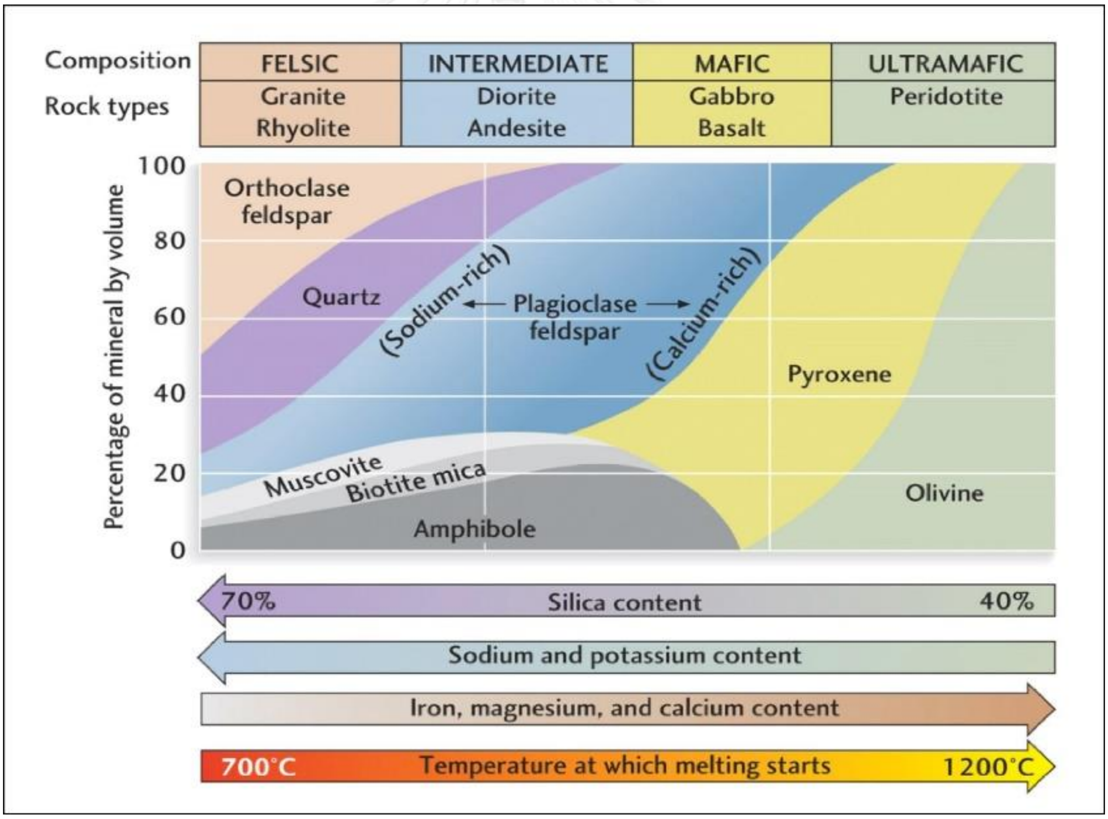


Figure 2-1: Igneous rock classification diagram, showing primary mineral composition of basalt and other magmatic rocks [5]

The nature of magma and its formation environments strongly influence to the variation of mineralogical and geochemical of basaltic rocks. Tholeiitic magma series is classified as sub-alkaline magma which contains less alkali than calc-alkaline magma series. As it cool, tholeiitic magma preferentially crystallize iron-poor and magnesium-rich mineral which lead to enrichment of iron content in the magma. Tholeiitic basalt commonly forms in the mid-oceanic ridge environment, called mid-oceanic basalt (**MORB**). Calc-alkaline basalt, on the other hand, contains less magnesium and iron content but higher alkali than tholeiitic series. Due to the precipitation of magnetite in the early stage of cooling, cause the ratio of magnesium and iron stable and whereby olivine starts crystalizing. Calc-alkaline basalt commonly found in continental collision, island arc and subduction zones. The present of olivine is one of the indicator to differentiate tholeiitic basalt from calc-alkaline. Magmatic series could be classified by AFM diagram (Figure 2-2) below [6, 7].

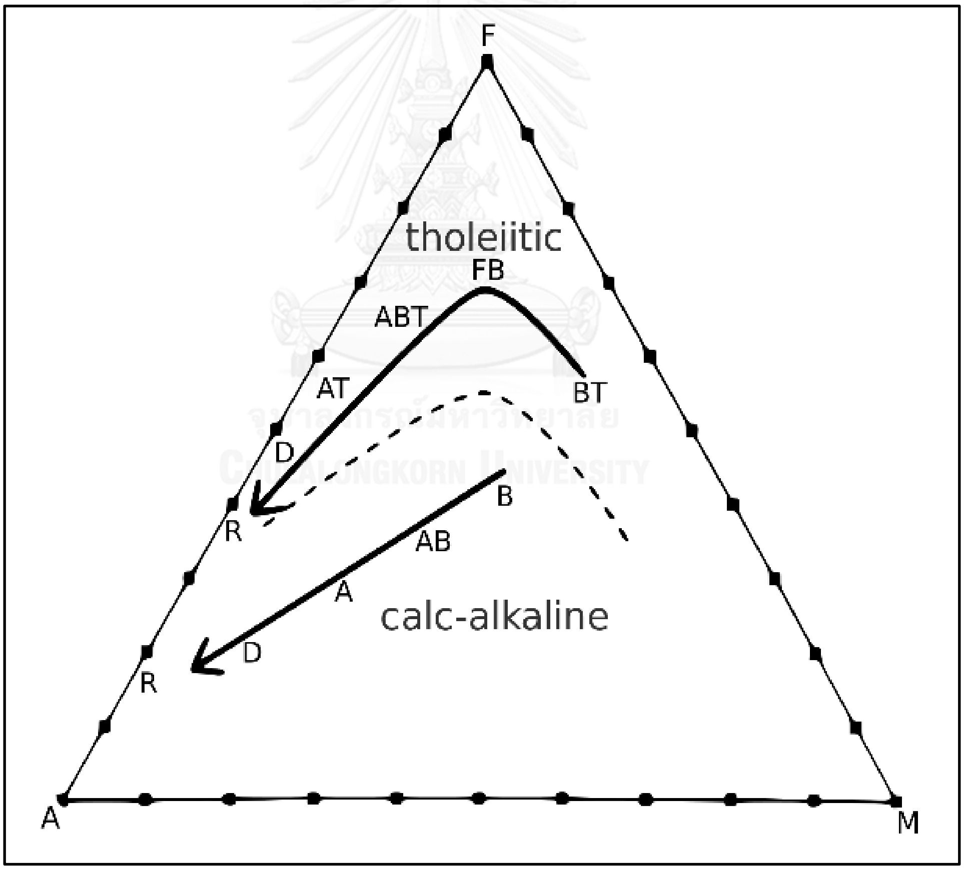


Figure 2-2: AFM (A: Na_2O+K_2O, F: Fe_2O_3+FeO and M: MgO) magmatic series classification diagram [6, 7].

Getting to know magmatic series of basalt provides preliminary ideas on the geochemistry behavior of the rocks being studied for making basalt fiber. From geological stand point calc-alkaline series basalt contains higher silica and alkalis content which is convenience for melting and reducing chance for crystallization. With high SiO_2 content than tholeiitic series, calc-alkaline series basalt tend to be more viscous and requires higher temperature to melt, but it produce higher strength and less crystal fiber. At the meantime, containing higher amount of alkalis can reduce melting temperature and as result cal-alkaline basalt tend to be good for producing higher quality fiber.

2.1.2. Characteristics of Basaltic Rocks Respected to Basalt Fiber Manufacturing

Table 2-1: Example oxides composition of basaltic rocks

Oxides	[8]			[9]			
	A	B	C	D	E	F	G
SiO_2	45.83	49.92	47.29	50.42	53.54	49.03	50.61
Al_2O_3	8.92	15.96	16.85	11.82	14.12	12.58	16.75
CaO	9.34	10.52	10.39	8.84	6.6	9.93	9.07
MgO	18.35	8.22	6.50	10.58	6.7	5.47	4.65
Fe_2O_3	3.39	2.80	9.87	-	-	-	-
FeO	7.48	6.44	-	9.43	7.64	10.15	3.6
K_2O	0.09	0.64	0.96	0.52	1.04	0.66	1
Na_2O	1.43	2.21	3.61	2	3.8	2.34	3.88
TiO2	0.52	0.68	0.61	1.04	1.52	2.85	1.81
MnO	0.20	0.13	0	0.18	0.2	0.32	0.18
P_2O_5	-	-	-	0.21	0.22	0.21	0.24
LOI	-	-	-	0.42	0.32	0.96	0.55

Pisciotta et al. (2015) and Morozov et al. (2001) studied the applicability of their basalt samples by oxides contents shown in table 2-1. Containing significantly high MgO and $FeO+Fe_2O_3$ with low SiO_2+ Al_2O_3 and Na_2O+K_2O, Melanocratic basalt (**A**), considered tholeiitic series, was found unsuitable for continuous basalt fiber (**CBF**) due to high ability of crystallization, increasing brittleness to the fiber. With higher SiO_2 + Al_2O_3 , Na_2O+K_2O and lower MgO than Melanocratic basalt, Andesitic basalt (**B**) and

Calc-alkaline basalt (**C**), on the other hand, are suitable for making fiber due to higher acidity modulous and appropirate visocity [8]. Morozov discovered that his samples (D: Myandukha basalt, E: Kondopoga Basalt, F: Berestovetskoe Basalt and G: Marneul'skoe Basalt) are within acceptable range of oxides' composition for making fine staple basalt fiber and good quality continuous basalt fiber [9].

United States patent has investigated basalt fiber quality for thermal insulation application by mixing raw materials with few pure oxides of basalt to achieve high insulation capacity and low crystallization ability. In their report they have classified basalt into two main categories (basalt ore for high and intermediate temperature), according to range of oxide composition [7]. By mixing 85% of high temperature ore and 15% of intermediate ore, another range of ore is achieved (see Table 2-2).

Table 2-2: Oxides content (wt.%) of basalt ores classified by United State Patent [10]

Oxides	(i) Ore (for high temp.) wt.%	(ii) Ore (for intermediate temp.) wt.%	85 wt.% of (i) + 15 wt.% of (ii)
SiO_2	57.1-61.2	54.0-58.2	57.7-60.6
Al_2O_3	16.1-19.2	14.9-18.1	16.5-18.9
$FeO+Fe_2O_3$	8.0-9.7	8.1-9.6	7.7-9.6
CaO	5.5-6.8	7.5-8.8	5.8-7.0
Na_2O	2.8-3.3	2.2-2.9	2.6-3.2
K_2O	1.8-2.1	1.4-1.8	1.8-2.2
MgO	0.20-2.5	1.4-4.8	0.2-2.8
TiO_2	0.7-1.0	0.8-1.1	0.1-0.3
MnO	0.1-0.3	0.1-0.3	0.1-0.3
P_2O_5	0.1-0.3	0.1-0.3	0.1-0.3
B_2O_3	0.1-0.3	0.04-0.20	0.04-0.3

2.1.3. Characteristics of basalt fibers

Although basalt fibers have similar composition comparing to glass fiber it has better mechanical properties, and higher resistivity to heat, alkalinity, acidity and salinity. These outstanding characteristics make basalt fiber to be a good material for reinforcing concrete, polymer and steel etc. Relatively a newcomer in fiber reinforced polymers (FRPs) and structural composites, basalt fiber exhibits better abrasion property comparing to asbestos. Under abrasion of the basalt fiber-woven fabrics over the propeller-type abraders, continuous basal fiber (CBF) can only break individual fibers from woven, but do not result in the splitting of fiber by fracture, which eliminates possibility of causing hazards. It also has the features of wider application-temperature range [-269 °C to 650 °C], higher oxidation resistance, radiation resistance [11, 12]. In their study on characteristics of basalt fiber as a strengthening material for concrete structures, Jong-Sung et al. (2005) [13] found that basalt fiber has strengthened their concrete structure better than E-glass due to its quality to withstand with heat, alkalinity and even weathering.

Table 2-3: Characteristics of basalt fiber comparing to other fibers [1, 14].

Characteristics	Fibers				
	Basalt	E-glass	S-glass	Carbon	Asbestos
Tensile strength, MPa	3000 - 4840	3100 - 3800	4020 - 4650	3500 - 6000	1,100 – 4,400
Elastic modulus, GPa	79.3 - 93.1	72.5 - 75.5	83 - 86	230 - 600	60 – 110
Elongation at break, %	3.1 – 6.0	4.7	5.3	1.5 - 2.0	-
Specific gravity	2.65 - 2.8	2.5 - 2.62	2.46	1.75 - 1.95	2.55
Filament's Diameter, µm	6.0 - 21.2	6.0 - 21.1	6.0 - 21.0	5.0 - 15.0	0.0008 – 1.2
Temp. of application, °C	-260 ~ 500	-50 ~ +380	-50 ~ +300	-50 ~ +700	-
Melting Temp., °C	1450	1120	1550	-	1200 - 1500

Basalt required no additives and consumed less energy to make fiber, resulting in cheaper and more reliable than glass fiber and carbon fiber. Natural basalt rock, the only raw material for basalt fiber production, is melted at 1450-1500 ^{o}C in furnace. The molten lava of basalt is passed through a continuous spinning process where a platinum/rhodium crumble brush basalt to create great reinforcement materials in form of chopped or continuous fibers, which is potentially can be used in textile and composite field [2].

2.1.4. Applications

Basalt materials do not absorb radioactive radiations, which makes them to be considered as the potential in production and transportation of radioactive materials, in nuclear power plants [1].

It has also been used as reinforcement for concrete materials. Basalt fiber can significantly improve deformation and energy absorption capacities of geopolymeric concrete while there is no notable improvement in dynamic compressive strength [15]. The basalt rebars consisting of 80% of basalt fiber with on epoxy binder offer better mechanical property to the reinforced concrete and are less expensive.

Chopped fibers are used in cement concrete which increases crack resistance and fracture toughness of concrete [1]. Due to their ceramic nature and to lower price than other ceramic fibers, basalt fibers represent a good candidate as reinforcing components also in metallic matrices. Nevertheless, the applicability of basalt fiber as a reinforcing material for metal matrix composites (MMCs) has been marginally investigated [16, 17].

High pressure pipes can be manufactured through filament winding, using fabrics and prepegs impregnate with a binder. These pipes are useful as components for transporting corrosive liquid and gases [1].

Scientist have been investigating properties of basalt fiber reinforced polymer and desired properties have been proven. Studies are conducted for all thermoset, thermoplastic and biodegradable polymers [17].

Due to their optimal properties, basalt fibers could be widely applied to many fields, such as corrosion resistance stuff in the chemical industry [18], wear and friction stuff in the automobile industry [19], target area of anti-low velocity impact [20], reinforcing material in construction [3], and high temperature insulation of automobile catalysts [21], fire protection and resistance [22].

2.2. Geology of study area

2.2.1. Regional Geology

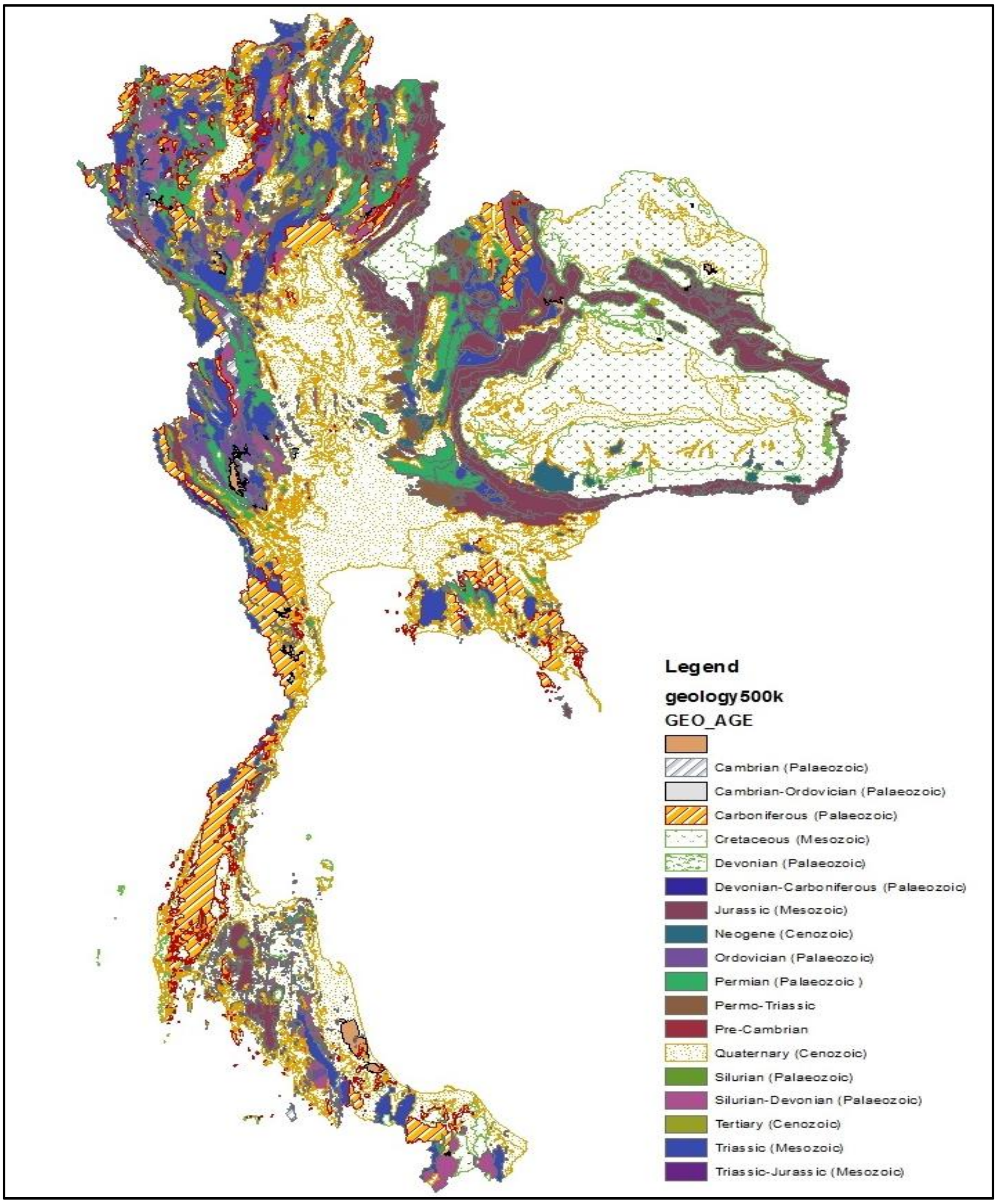


Figure 2-3: Map showing age of geological formations in Thailand

Geology of Thailand comprises of various geologic units which had been developed through time. The central part of Thailand is dominantly covered by Quaternary alluvial sediments concealing underlain ancient geologic features. Pre-

Cambrian, which believe to be the bed rock of Shan-Thai and Indosinia blocks, found at southern part, while the southeastern part covered mainly by carboniferous rocks. Western and northwestern area, which is a part of Sinoburmalaya block, covered by geological formations with wide range of age from late Paleozoic to late Cenozoic and some Quaternary alluvial sediments. This reflects the present of subsequence geologic evolution in the terrane during regional scale tectonic activities. Khorat basin is a gigantic geologic feature in Thailand which is believe to be a part of Indosinia cratonic block. After being sutured in Jurassic between Shan-Thai and Indosinia, the continental rifting occurs at the Indosinia continent forming the basin and introduced volcanic activity in Lopburi province which is situated in the central part of Thailand, southern part of the Loei-Phetchabun fold belt and adjacent to the edge of Khorat basin (Figure 2-3).

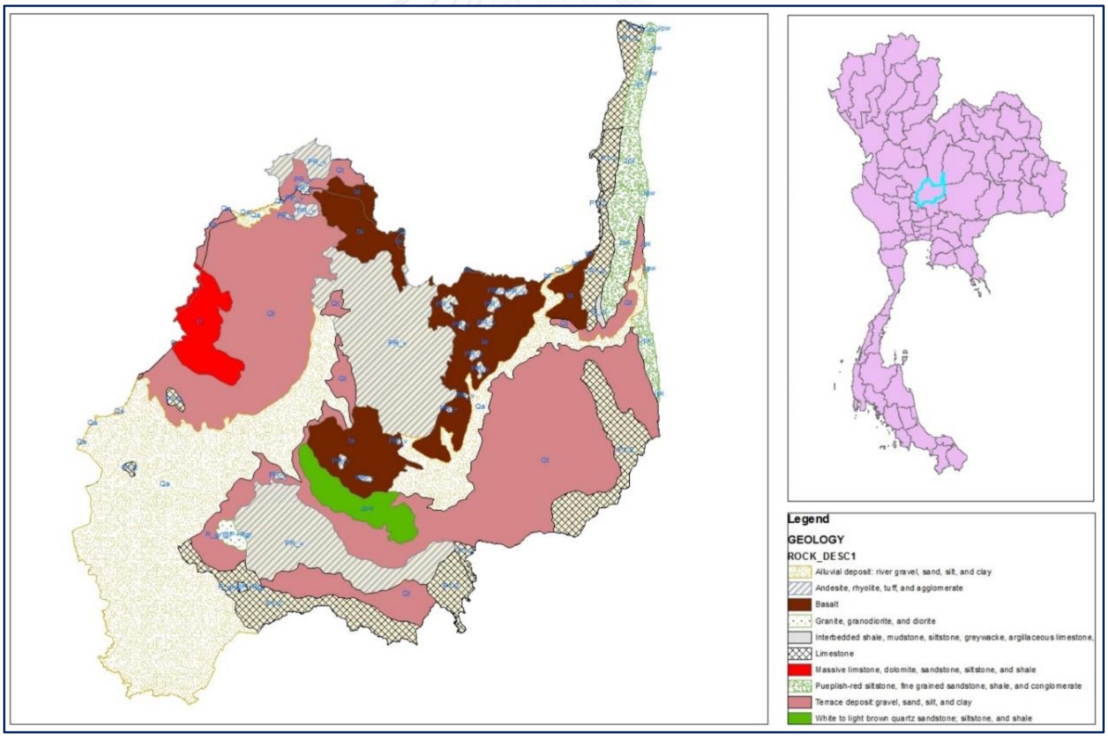


Figure 2-4: Geological map of Lopburi Province, Thailand

As shown in the map (Figure: 2-4), Lopburi province was covered almost two-third of the total area by Quaternary alluvial deposits and terrace gravel, sand, silt and clay deposits. Permian limestone, formed prior to the closing of oceanic floor between Shan-Thai and Indosinia, are found southeastern, northwestern and northern border of the province. Two major sedimentary rock units had formed in Jurassic period present: 1. at the northeastern next to Permian limestone and 2. in central part. Nonetheless series of volcanic rock are found in the center of the province trending northeastern to southwestern. Andesitic – rhyolitic tuff and agglomerate were formed in Permo-Triassic and basaltic rocks formed in Cenozoic were found dominantly cover the central part of Lopburi. Several Permo-Triassic bodies were found in surrounding by later basaltic rocks. This indicates that basaltic lava in Cenozoic might have flown over the Permo-Triassic rhyolitic bodies. There are also few small plugs of Triassic granitic rocks. These could be S-type granitic rock forming in back arc, during the subduction of oceanic plate to Shan-Thai crustal plate.

2.2.2. Tectonic Evolutions of Thailand

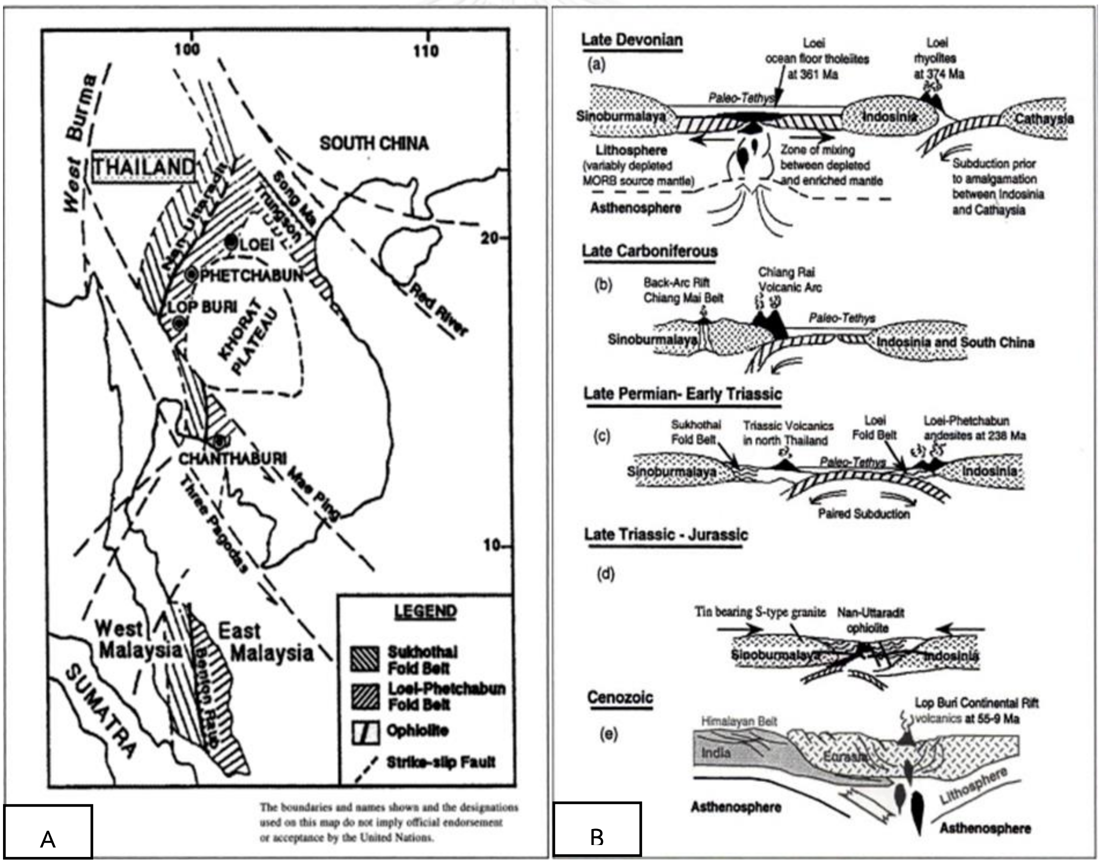


Figure 2-5: [A]: Lopburi formation is situate on the Loei-Phetchebun Fold Belt and on the Edge of Korat Basin. The Nan-Uttaradit and Loei-Phechabun Fold Belts Separated by Ophiolite Belt (Bunopas, 1981). [B]: Tectonic Evolution of Southeast Asia and Central Thailand

As part of Southeast Asia terrane (Figure 2-5), Thailand's geological setting is closely related to the tectonic evolution of the region. According to Metcalfe [23], Southeast Asia is constituted from four principles continental blocks: Cathaysia (South China), Indosinia (Indochina), Sinoburmalaya (Shan-Thai) and East Malaya. Out of these four cratonic blocks, Thailand extends over eastern part of Shan-Thai and western part of Indosinia. Although the stratigraphy sequences of the two microcontinents are similar, but they had independent geologic histories prior to suturing. The Shan-Thai which is an elongated block was derived from northwest Australia Gondwanaland with Pre-Cambrian basement, while Indosinia is believed to be a long time stable continent.

Volcanic activities in central Thailand has very strong relationship to Loei-Phetchabun belt which had been developed through several episodes. The subduction, suturing and subsequent continental collision from Middle Devonian to Late Tertiary introduced volcanic evolution along the belt. Forming in a single volcanic arc, volcanic rocks in this area were not formed in the same geological period. Intasopa [24] demonstrated that there were three major period of magmatic evolution: Late Devonian-Early Carboniferous, Middle Triassic and Tertiary. Accordingly, Bunopas [25] suggested that volcanic activities are related to Paleozoic subduction.

After the rifting of Cathaysia and Indosinia in Silurian or Devonian [26], the South China block rapidly subducted and collided the Indosinia block, suturing to be a single terrane from late Devonian to early Carboniferous, forming Troungson fold belt [27]. Volcanic arc in northern Thailand was form during late Carboniferous due to the subduction of oceanic plate between Indosinia and Shan-Thai. Prior to suturing between Shan-Thai and Indosinia, paired subduction occurred in late Permian or early Triassic forming Loei-Phetchabun fold belt and Triassic volcanic arc in northern Thailand. Nan-Uttaradit fold belt at the Shan-Thai edge uplifted in late Triassic or Early Jurassic upon the suture of between Shan-Thai and Indosinia blocks. Nan-Uttaradit fold and Loei-Phetchabun fold mountain range are separated by ophiolite belt, resulting from uplifted mental rock while colliding. After colliding and be a single block, Lopburi continental rifting occurred within Cenozoic, the process by which formed the Korat basin and Lopburi volcanism.

2.2.3. Basaltic rocks in Lopburi Province

Collision, suturing and continental rifting, influenced from regional tectonism, give rise to a series of volcanic activities in central Thailand. In Early Eocene, approximately 55 Ma, suturing of Greater India and Southeast Asia had completed, while continental rifting had been initiating at 52 Ma [19]. The two sequential processes introduced Lopburi Rhyolitic Magmatism dated back at 57-55 Ma. Displacement of left lateral Red River Fault in Early Miocene [28] generated mildly alkali basaltic, trachyandestic and rhyolitic volcanism in Lopburi area at 24.1, 23.7 and 22 Ma respectively.

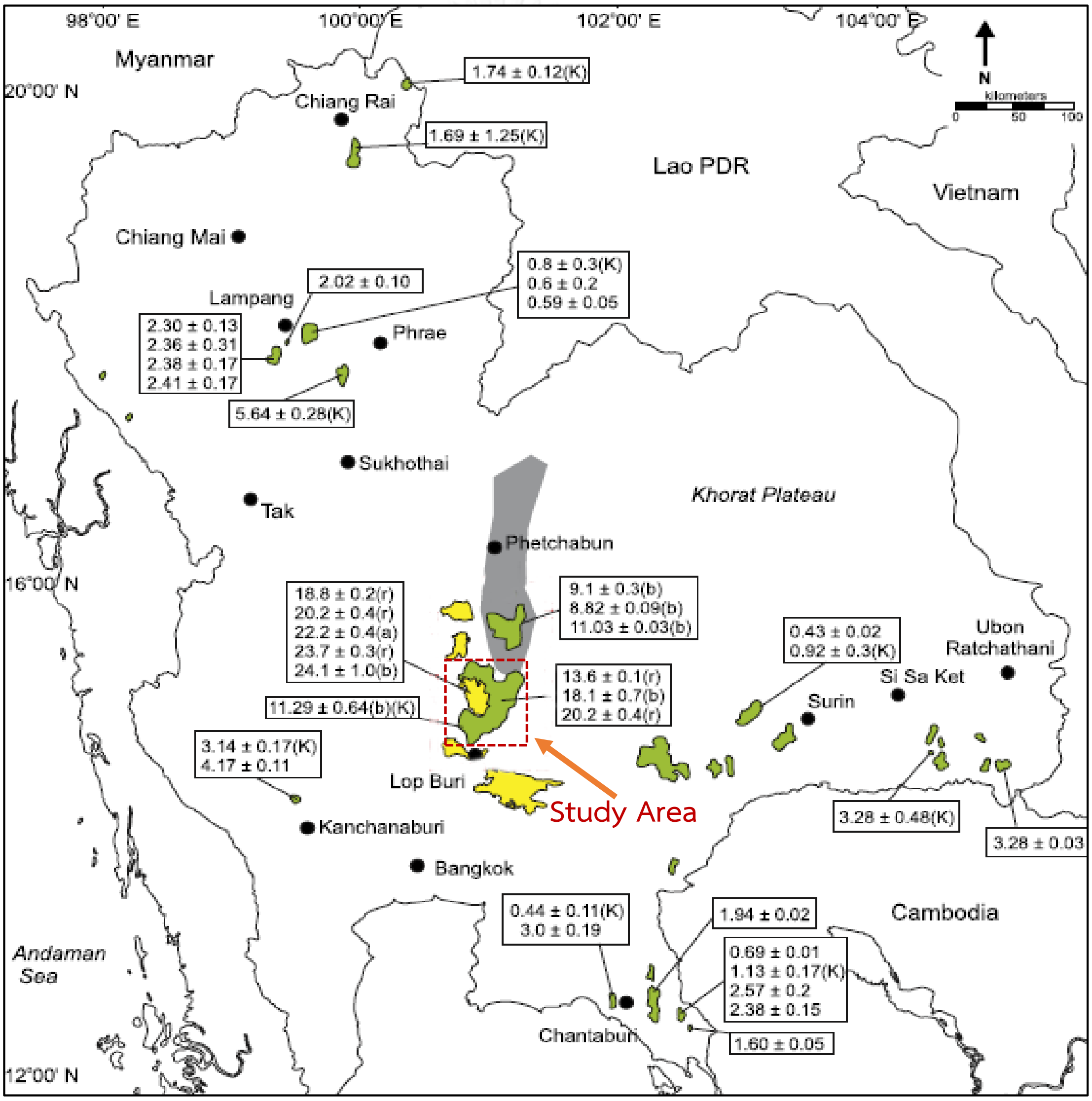


Figure 2-6: Map showing Cenozoic volcanic rocks in Thailand

Hooper [29] dated rhyolitic volcanism in southern Chao Phraya Plain at 22.5 Ma. Accordingly, in Middle Miocene (22 Ma), there was widespread depression of Cenozoic basins [30]; the process by which developed another rhyolitic magmatism in Lopburi. According to Intasopa [24], there are series of later distinct magmatism: Alkali basalt (18.8 Ma), andesitic (18 Ma) and rhyolitic (13.6-9.1 Ma). Volcanic activities in Lopburi did not finish until 11.29 Ma (Alkali basaltic magmatism) as dated by Barr and McDonald [31].

Basaltic rocks in Lopburi area had formed in various episodes in Cenozoic, inter-sequentially with andesitic and rhyolitic (see Figure 2-6). Based on geological map (Figure 2-4) we clearly see that there are series of basaltic and rhyolitic bodies intersecting each other. From history of volcanism activities summarized above, it has been noticed that basaltic and rhyolitic rocks might be interbedded or covering each other in certain area. It increases high ability to have metamorphism or alteration process prior to their stability. This reflects the heterogeneity of basalt resources in the study area, which influence degree of certainty of estimation.

CHAPTER 3: MATERIALS AND METHODOLOGY

3.1. Research Methodology

The methodology of this research follows the normal work in order to evaluate a resource for a specific application as shown in the flowchart in Figure 3-1. It started from *desk study* with intensive literature review. A number of papers, books, as well as articles have been investigated. Then a couple field works had been done in the study area. Along with field works, several samples had been collected for later testing in the laboratory. After that all information and data have been studied carefully in order to evaluate the suitability of basalt resources in making basalt fiber. Finally, conclusions from this work and recommendations for further research had been made.

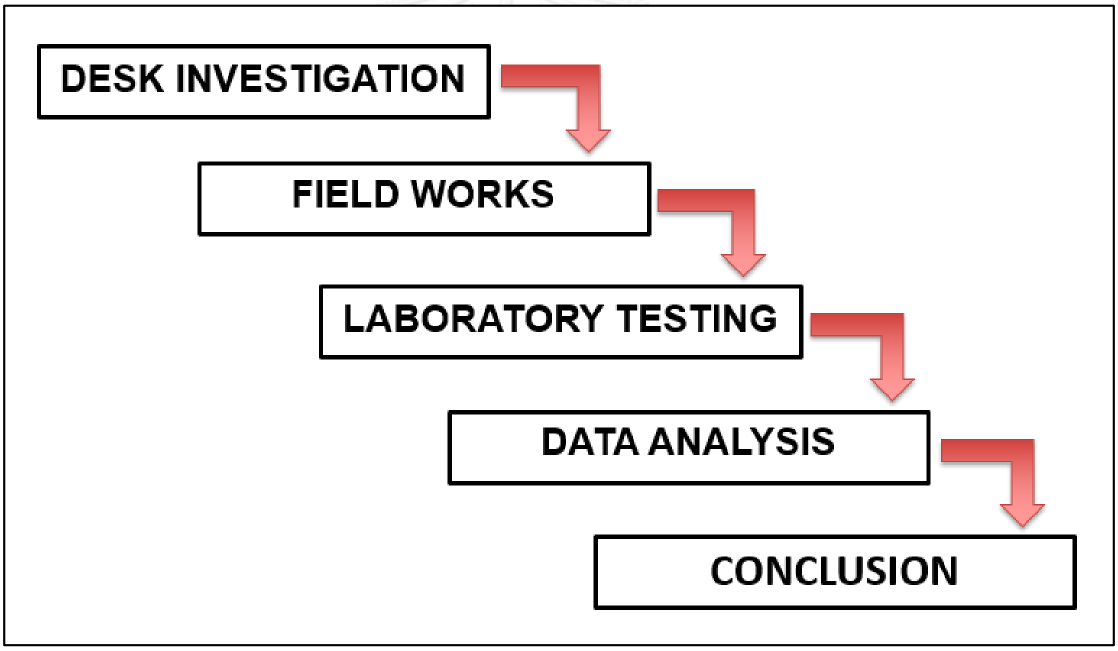


Figure 3-1: Work flows applied by this thesis

3.2. Field investigation

Primary field reconnaissance has been conducted in Khok Samrong and Chai Badan districts of Lopburi province. A number of hand specimens were collected. Second field trip was conducted during summer from April 5 to April 8, 2016 with geological survey team from Department of Mineral Resources of Thailand (DMR). During the two fieldworks, 21 representative samples were collected from three basalt tenements: Khok Chareon, Chai Badan and Khok Samrong Basalt. Basaltic rocks in the study area are preliminarily observed and classified during field investigation, based on their mineralogy and physical characteristics such as presence of primary and secondary minerals, colors, textures, degree of weathering and alterations.

3.3. Basalt Characterization

Representative samples are characterized by X-Ray Fluorescence (XRF) technique to analyze their chemical composition: SiO_2, Al_2O_3, FeO/Fe_2O_3, CaO, Na_2O, K_2O, MgO, TiO_2, MnO and P_2O_5. These oxides are used for analyzing the suitability for making basalt fiber by comparing with case studies conducted by Pisciotta et al., 2015 and Morozov et al., 2001 [8, 9]. Due to the limitation of fund and equipment, only 7 samples (KS-01, KS-02A, KS-02B, KS-03A, KS-03B, CB-01A, CB-01B) taken during field investigation was analyzed in Department of Mining and Petroleum Engineering laboratory. Other XRF data (LBS-01, LBS-02, LBS-03, LBS-04, LBS-05, LBS-06, LBS-07, LBS-08, LBS-09, LBS-10, LBS-11, LBS-12, LAN-01, LAG-01) were obtained from Department of Mineral Resources of Thailand.

3.4. Geochemistry data representation and analysis

Weight percentages of oxides, obtained from XRF analysis, are represented in tables and diagrams in statistical ways, in order to better understand nature of the geochemistry data as well for classification purpose. Variation analysis, total alkali-silica, and magmatic series classification are the principles methods used for classifying rock types in these three tenement. As secondary unit of measure, apart from geology, modulus of viscosity (M_v) and acidity (M_a) are calculated and compared against the case study results. According to the two modulus and US Patent standard, basaltic ores in Lopburi are going be grouped in order to observe its melting characteristics with a statistical model.

3.4.1. Variation analysis

Harker Variation Diagram is a common way to display geochemical data, especially major element oxides, in such comprehensive way and it’s very useful to differentiate various rock samples from similar geology. In this classification we use wt.% of major oxides of Lopburi and [8, 9] samples for plotting against SiO_2 wt.% and their variations are interpreted.

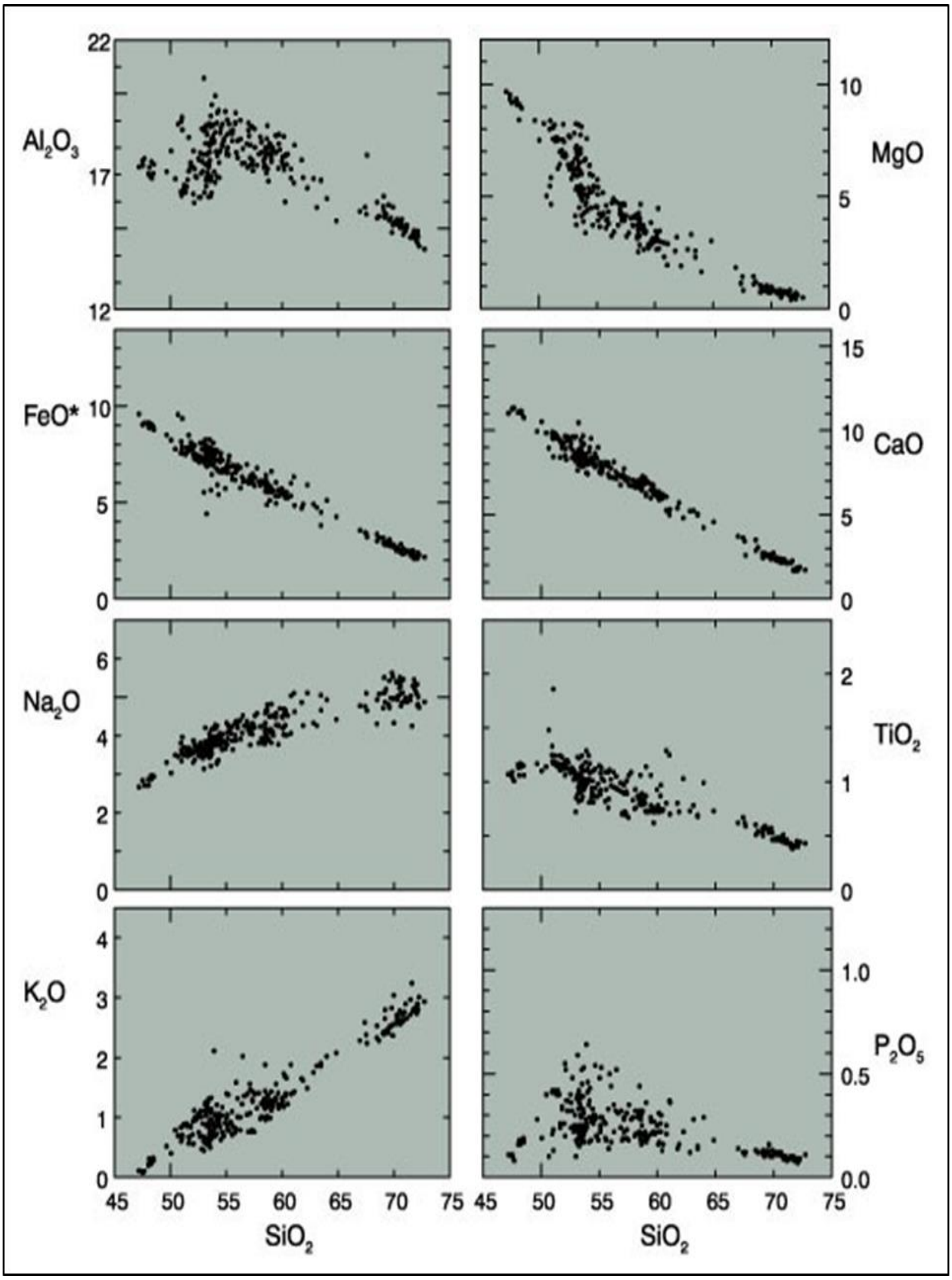


Figure 3-2: Example of Harker Variation diagrams of major oxides [32]

3.4.2. Total Alkali-Silica Classification

TAS is one of the most useful classification diagram for igneous rocks. Taken directly from major oxide data, total alkali (K_2O+Na_2O) wt.% is plotted against silica contents SiO_2 wt.% into classification scheme developed by [33, 34]. Differentiation sub-rock types of basalt at the field is a very confusing task, especially in the area, with complicate geological evaluation such Lopburi. The results from the classification would help to differentiate confusing rock types (basalt, andesitic basalt, trachy basalt, dacite and rhyolite). Total alkalis and SiO_2 wt.% of basalt from Lopburi are plotted with sample of [8, 9] to observe their geochemistry relationships.

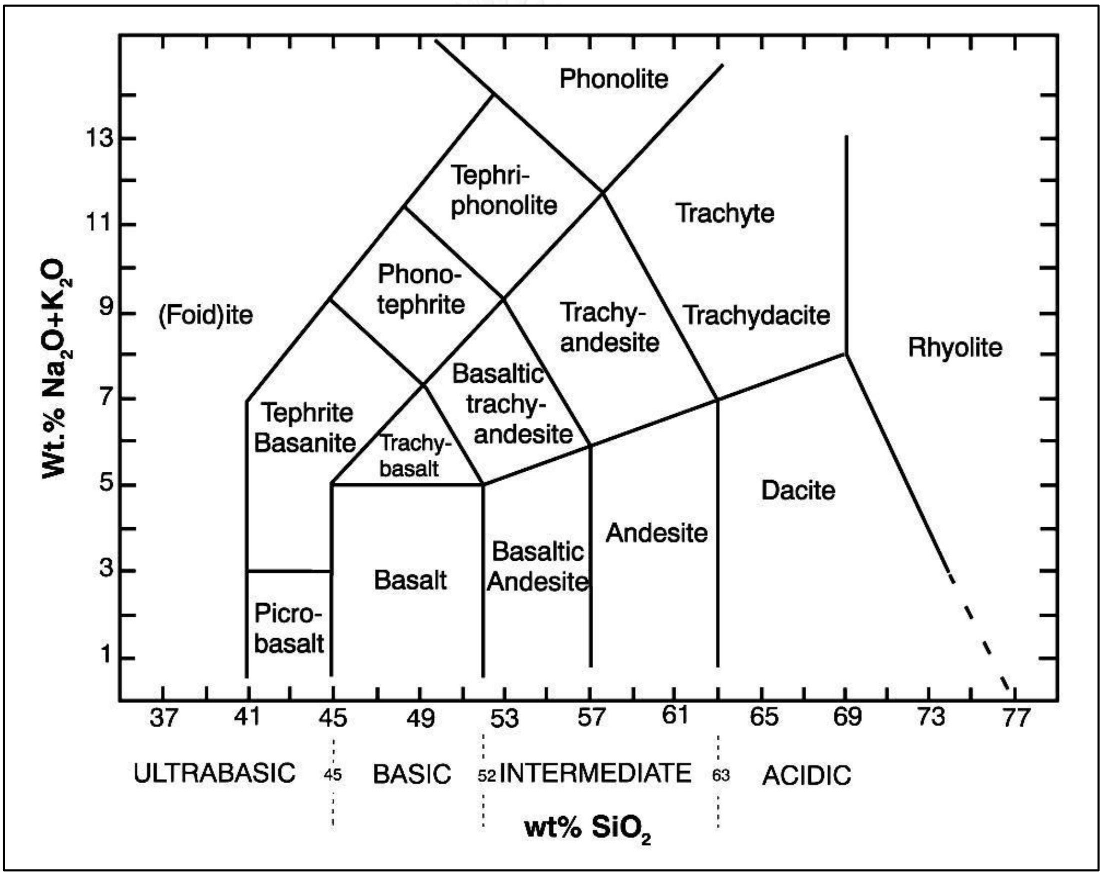


Figure 3-3: TAS classification diagram, after [33]

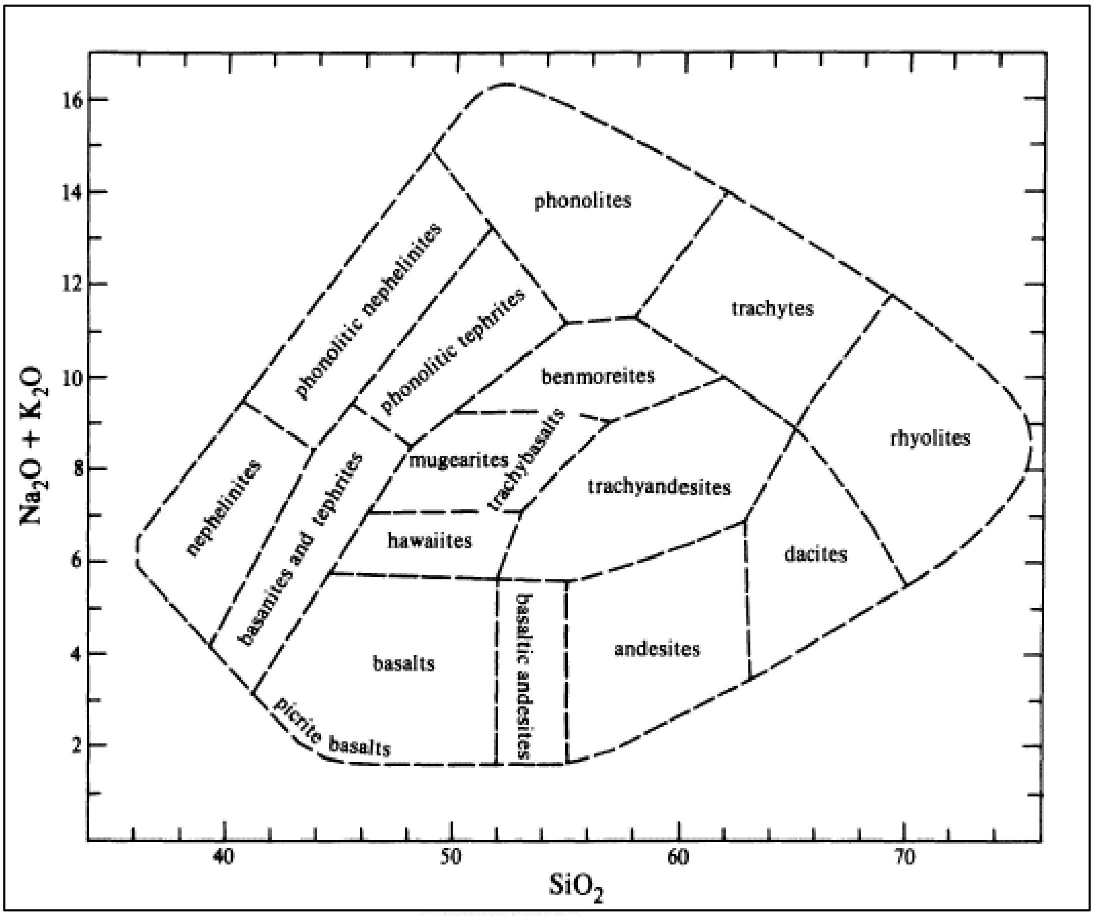


Figure 3-4: TAS nomenclature diagram for igneous rocks, after [34]

Although the two classification schemes use the same oxides, but their purposes are slightly different. Earlier developed TAS of [33] is a general lithological classification, while the TAS of [34] is a rock nomenclature classification, which differentiate rocks into greater detail. However, by using the two models together, we are able to make comparison and verification.

3.4.3. Magmatic series classification

Commonly basalts are originated from two main magmatic series, calc-alkaline series and Sub-alkaline series (Tholeiitic series). Geochemically, the different between the two series are the concentrations of alkalis (Na and K) and their formation environments. Tholeiitic series basalts are commonly associated with Mid-Oceanic Ridge environment, commonly known as MORBs (Mid-Oceanic Ridge Basalts), meanwhile calc-alkaline series basalts are associated with continental environments (back-arc, convergence plate boundaries, continental rifting and etc.).

Magma series can be classified by plotting [SiO_2-K_2O] wt.% (Figure 3-4) developed by [35] and AFM ternary diagram (Figure 3-5) developed by [6, 7]. [SiO_2-K_2O] classification diagram simply discriminates rocks into low-K basalt series (Tholeiitic basalt), calc-alkaline basalt series, high-K calc-alkaline series and Alkaline series. Getting to know magma series of basalt rock lead to the understanding of their geochemical behavior, which have direct impact to the suitability for making fiber. Having low concentration of alkalis, tholeiitic basalts are tending to be more viscous with the same range of SiO_2 and Al_2O_3 wt.%. Apart from ability to reduce viscosity, alkalinity make the fiber more resistance to alkalinity environments, but less stable in acidity. Though, Cal-alkaline basalt series increase chance of having lower viscosity, which is very critical in commercial manufacturing.

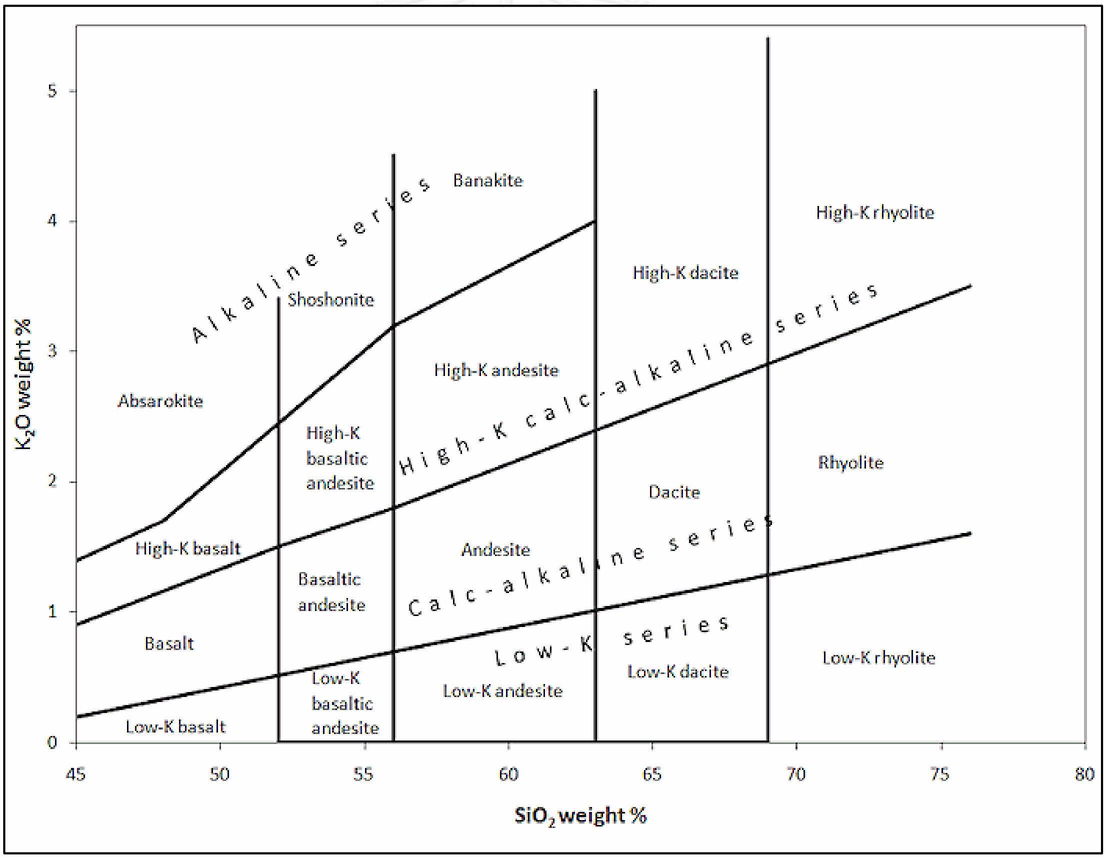


Figure 3-5 Magma series classification diagram, after [35]

During cooling process, tholeiitic magma series tend to precipitate noticeably more iron and magnesium, rather than alkalis. This phenomenon cause composition of magma to move away from magnesium and iron to the alkali corner. In early stage tholeiitic magma crystalline mostly Mg-rich crystal, depleting magnesium from the magma and elevating iron concentration, causing it moves to iron and then to alkali corner on the AFM diagram. On the other hand, calc-alkaline series tend to precipitate iron rich minerals such as magnetite, resulting in relatively constant iron-magnesium throughout the cooling process, proving straight line moving towards the alkali corner of AFM diagram (see Figure 3-5).

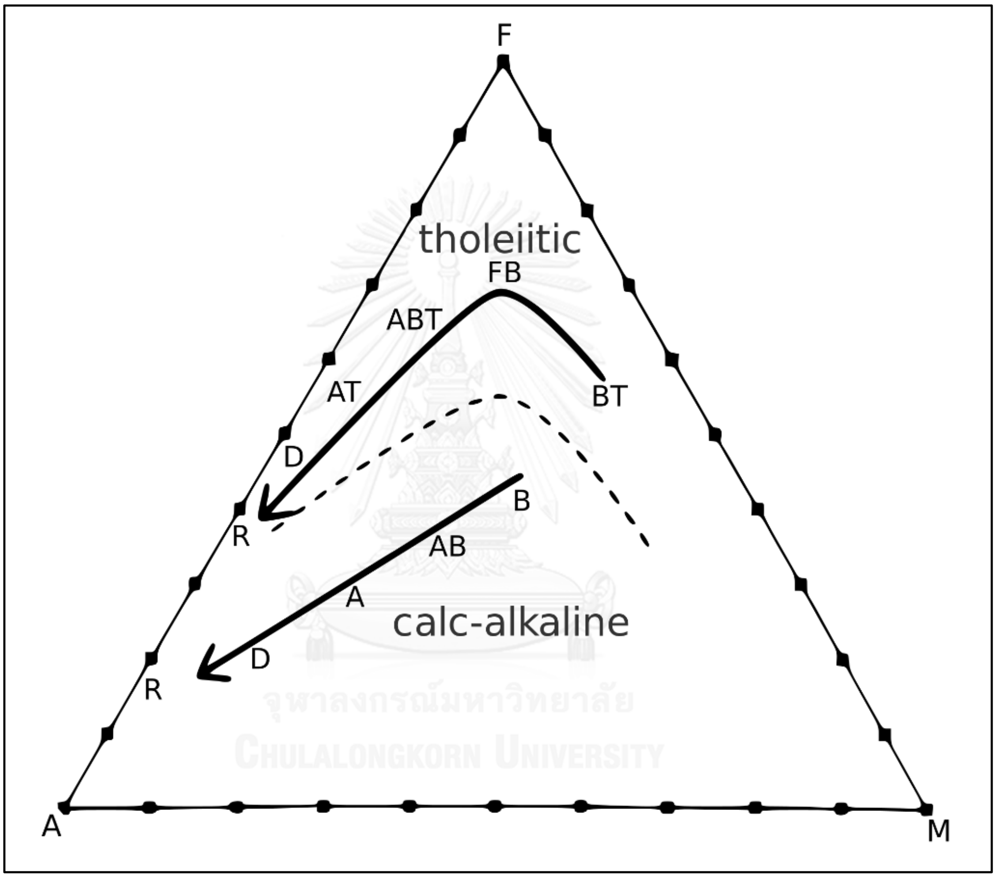


Figure 3-6: Example of AMF: Alkalis-Magnesium-Iron analysis developed by [6, 7]

High magnesium is a sign of having lower acidity, while iron content and alkalinity have increasing impact to viscosity. Too high iron content could lead to highly crystalline fiber, which is the main cause of brittleness.

3.4.4. Acidity and Viscosity Modulus

Acidity modulus (M_a) which indicates quality of fiber is calculated from oxide contents. According to Pisciotta et al., (2015) and Morozov et al., (2001): if M_a < 1.2, the resultant fiber is called slag wool, which is brittle, very poor strength and chemical resistance; if 1.2 < M_a < 1.5, the resultant fiber is called mineral wool, which is brittle (low strength) with acceptable insulation capacity; if M_a > 1.5, the fiber is called rock wool (basalt wool) with high elasticity modulus, excellent heat resistance and sound absorbing property. In US Patent report about basalt fiber material [10], select M_a greater or equal 3.0 and viscosity modulus (M_v) greater or equal 1.5 as minimum criteria for their basaltic ore for high and intermediate temperature application.

Equation 1: : Acidity Modulus and Viscosity Modulus [10]

$$M_a = (Al_2O_3 + SiO_2) / (CaO + MgO) \geq 3$$
$$M_v = (2Al_2O_3 + SiO_2) / (2Fe_2 + FeO + CaO + MgO + K_2O + N_2O) \geq 1.5$$

3.5. Melting curve analysis

A set of outstanding samples was selected among Lopburi basalt for estimating their viscosity at commercially applicable melting temperature, which according to [2] is within the range of 1450 – 1500 °C. Log[viscosity] of basalt melt through temperature range was calculated using model produced by Statistical Calculation and Development of Glass Properties. In his study on basalt fiber, Apirat (2016) has modified his basalt sample (Table 5), B02 to BG01 for achieving lower temperature and viscosity in order to reduce production cost (Apirat 2016). Viscosity curves of selected basalt samples are plotted with the two samples of [36] for comparison purpose. Acceptable Log. viscosity at temperature of 1450 - 1500 °C is recommended to be within 2.0-3.0 (Pa*s) or below.

In his study Dr. Apirat [36] used raw basalt sample **(B02)** and modified sample **(BG01)** by adding dolomite to enhance SiO_2, CaO, MgO, Fe_2O_3 and Na_2O for melting test. The result from his study indicates that the modified sample **(BG01)** could be completely melt at temperature of 1190.10 °C with Log. Viscosity as low as 2 Pa*s. Meanwhile, raw basalt sample exhibits relatively higher melting temperature and viscosity (1365.10 °C @2 Pa*s). However, both sample appear to be able to completely melt at temperature less than 1500 °C, which is acceptable temperature range for basalt fiber production. (see Table 3-1 & 3-2 and Figure 3-6).

Table 3-1: Samples studied by [36]

Samples	SiO2	Al2O3	CaO	MgO	Fe2O3	K2O	Na2O	TiO2	MnO
BG01	48.16	18	12	4	10	2.18	4	1.38	0.18
B02	53.31	18.1	8.1	2.3	9.8	2.18	4.55	1.38	0.18

Table 3-2: Log. Viscosity vs. temperature of basalt samples conducted by Apirat et al., 2016 [36], using statistical worksheet developed by www.glassproperties.com

Log. Viscosity	B02	BG01
1.10	1616.40	1399.80
1.50	**1476.6**	**1281.2**
2.00	1365.10	1190.10
3.00	1198.40	1059.60
4.00	1079.80	970.60
5.00	991.00	906.60
6.00	922.10	856.90
6.60	**887.70**	**832.80**
7.00	867.10	818.50
8.00	822.20	787.40
9.00	784.70	761.40
10.00	758.10	740.50
11.00	726.00	722.40
12.00	702.50	**706.80**
12.30	696.10	702.50
13.00	682.00	693.20
13.50	672.70	687.10

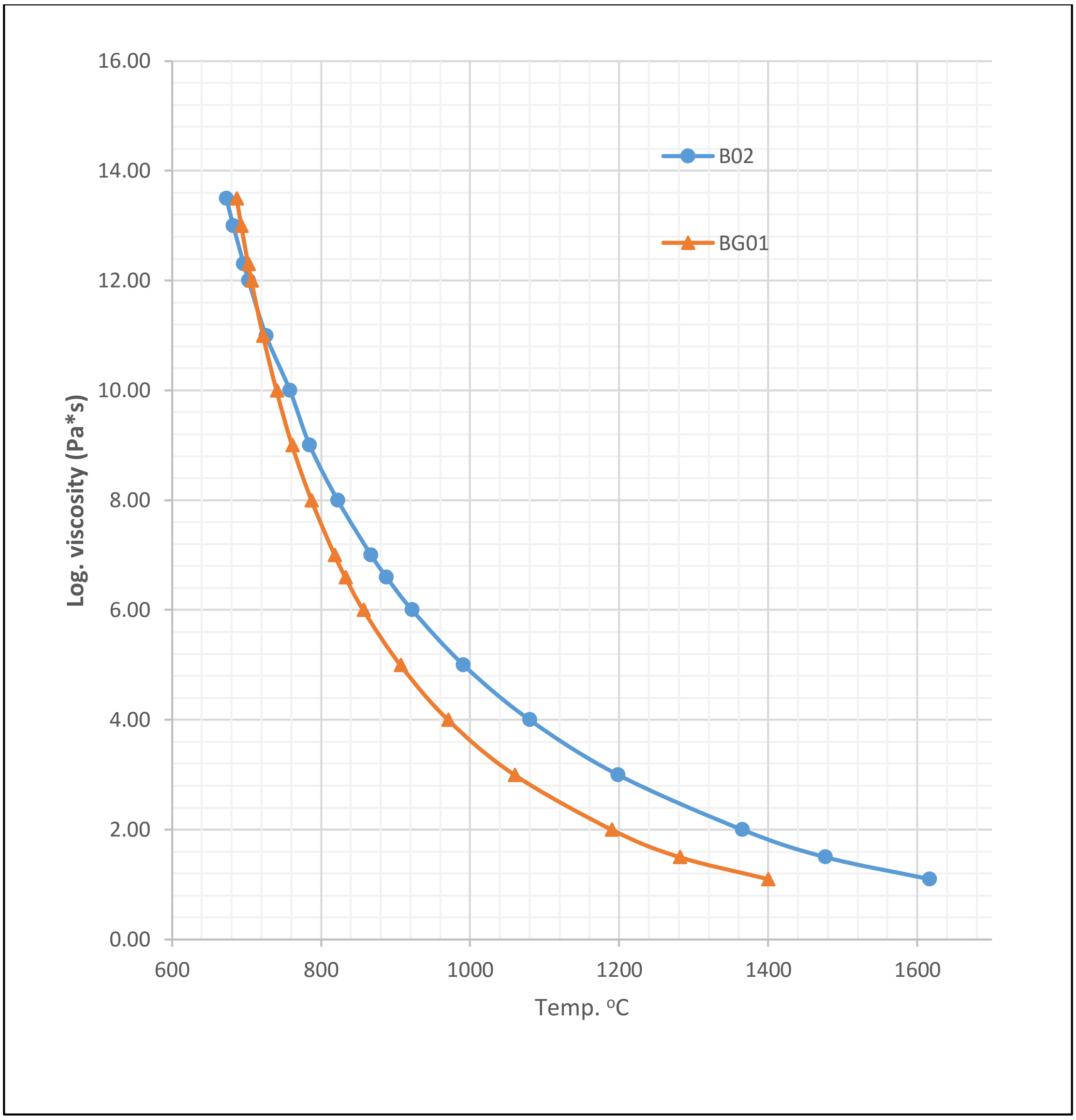


Figure 3-7: Viscosity curves of basalt samples of [36], statistically calculated using excel worksheet of www.glassproperties.com

CHAPTER 4: RESULTS AND DISCUSSION

4.1. Geological field investigation

Lopburi basalt is divided into three tenements namely, Khok Chareon, Khok Samrong and Chai Badan (see Figure 4-1), due to their separated extent over these districts. As having been discussed in the geology of study the area section, basalt in Lopburi has been formed from discrete periods during Cenozoic suturing and rifting of Indosinia cratonic block. Between periods of basalt volcanism there are also andesitic to rhyolitic magmatism occurred in the same geological environment, which may be resulted from periodic mantle melting and fractionation during the development of basins. Multi-sequences magmatism with different composition (basaltic, andesitic and rhyolitic) may have overlapped or interbedded in certain area, causing alteration and metamorphism, making it more vulnerable to weathering.

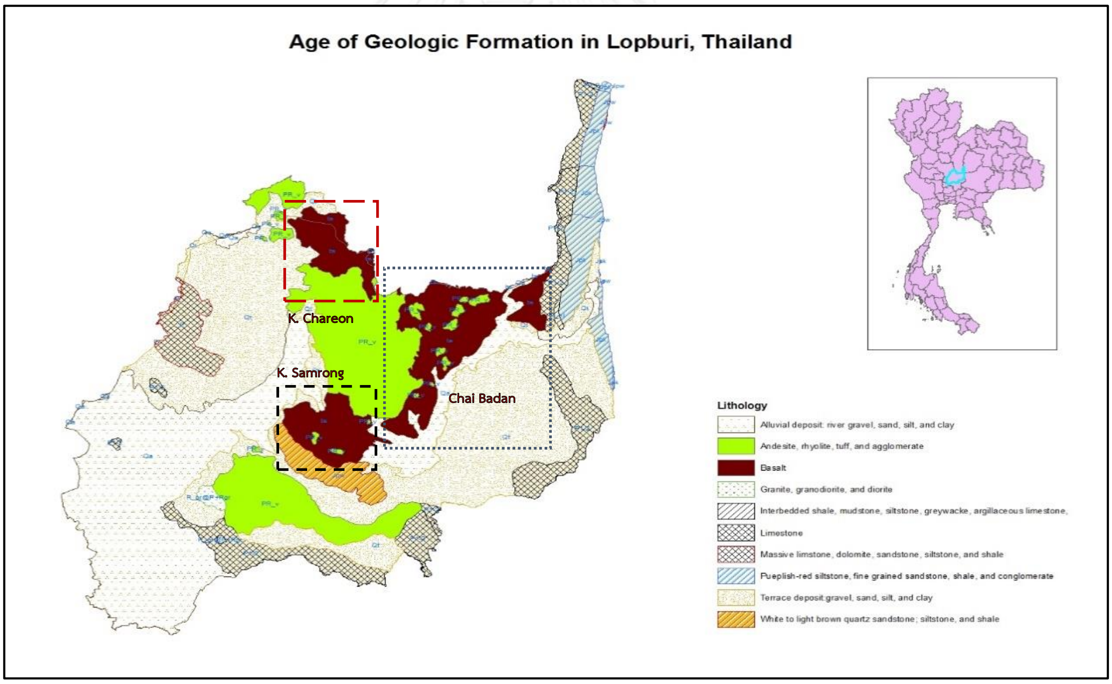


Figure 4-1: Map showing geological formation and tenements of Lopburi Province

As observed during field investigation, physical properties of basaltic rocks are considerably varied. Not so different from other basalt terrain in Southeast Asia, Lopburi basalts are mechanically and chemically weathered, making it hard to find outcrops. Floated basalt boulders are the most common outcrop found entire the field. However, numbers of excavated wells for irrigation purposes are found in many poor outcrop areas, allowing us to access concealed basalt layers beneath the soil.

4.1.1. Khok Chareon tenement

Basaltic rocks in Khok Chareon district are located northwestern of Lopburi province and bounded by Quaternary sediments and andesitic to rhyolitic tuffs at southern to southwestern parts. Khok Chareon basalt was mapped as continuous terrain with absence of interruption of other lithology and the area was observed as having very poor outcrop (Figures 4-2). Mostly, the surface of the terrain is covered by basaltic-gravel bearing soils and small to medium size of basalt fragments and boulders. Numbers of excavated wells for irrigation purposes help to expose very good and more detail physical characteristics of outcrops. Some basaltic outcrops are also found as eroded bodies which covered by boulders. However, from physical observation fives group of rocks was found across the terrain: 1. firmly dense basalt, 2. weak and brittle weathered basalt, 3. andesitic basalt, 4. platy-brittle rock and 5. vesicular basalt (see Figure 4-3).

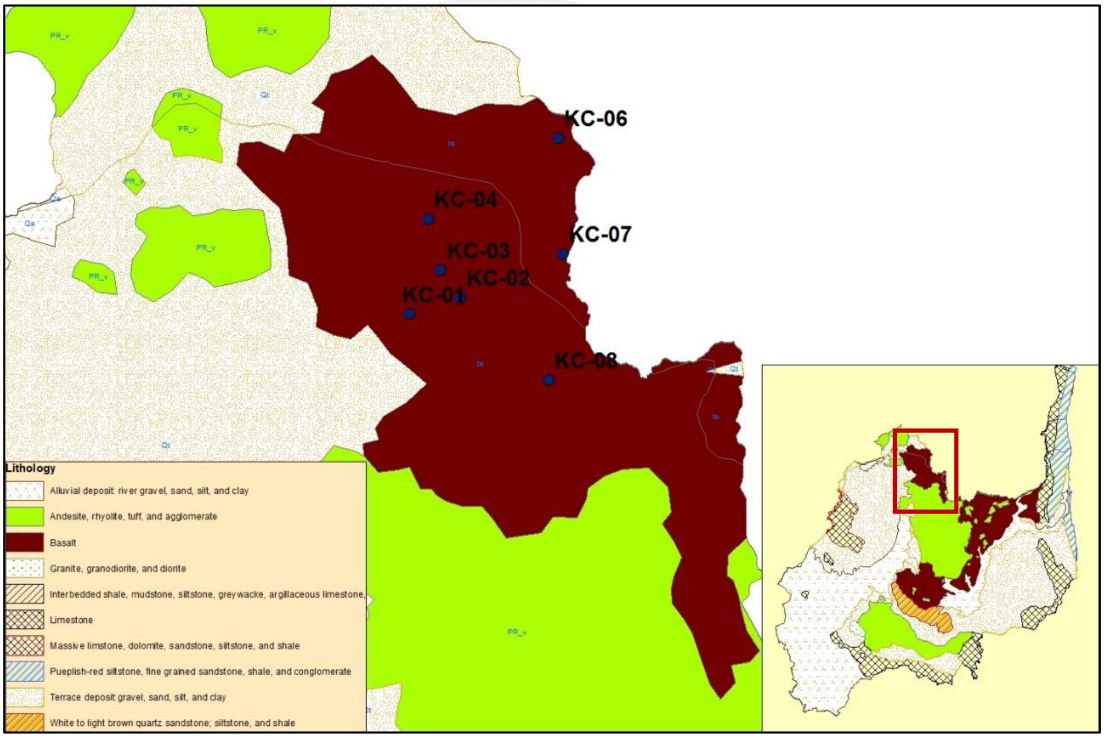


Figure 4-2: Map showing basalt terrain sampling points and outcrops in Khok Chareon

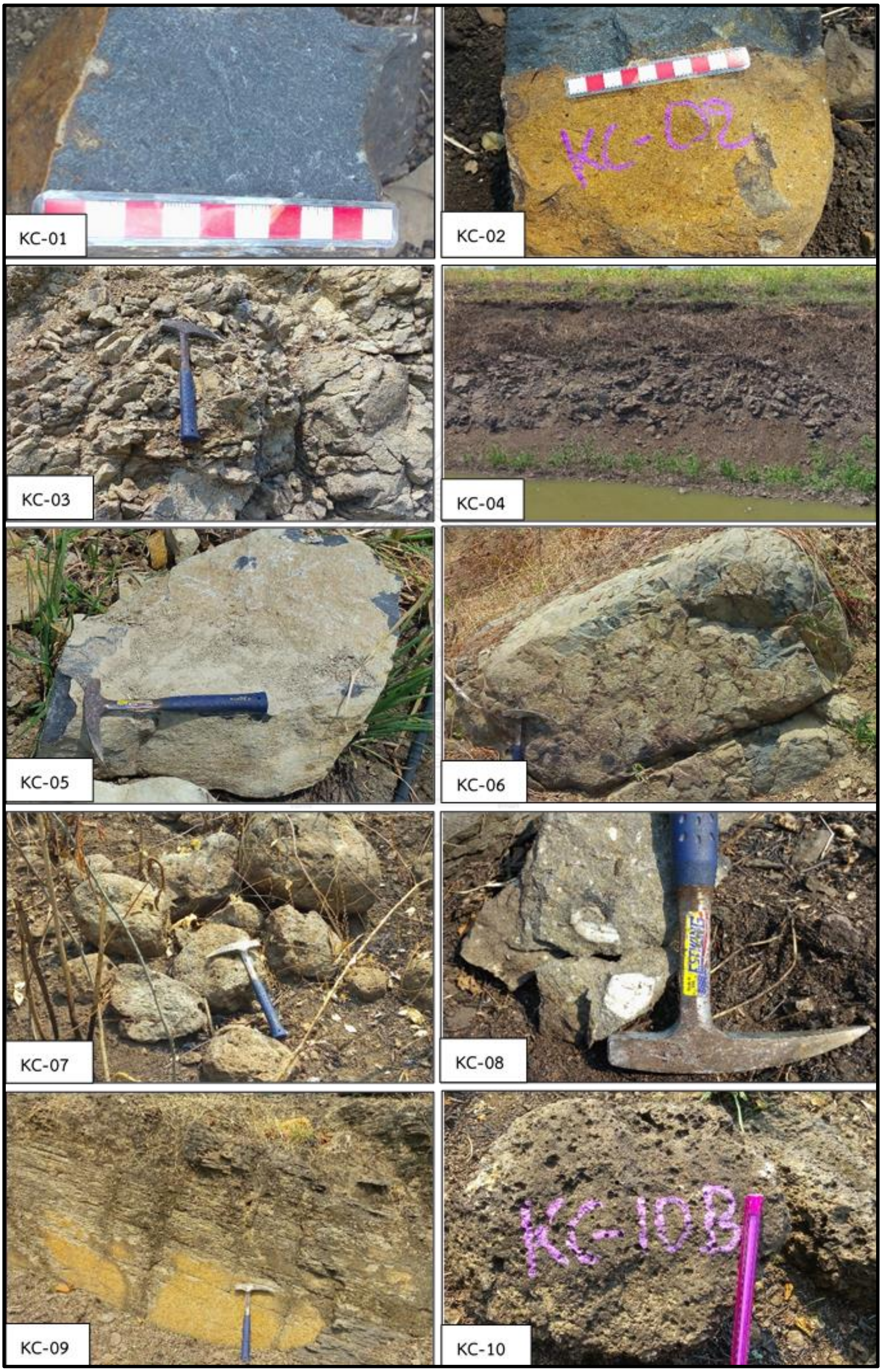


Figure 4-3: Showing rock samples and outcrops from Khok Chareon tenement

As shown in Figure 4-3, basalt samples, **KC-01**, **KC-02** and **KC-05,** remain fresh and firmly dense. These three samples occurred to be gray to dark-gray in color, and very fine-grained, non-vesicular texture. Basalt samples, **KC-01** and **KC-02,** was found as float basalt boulder over cassava field. Laminated texture was observed on **KC-02,** while **KC-01** is very strong and massive. Very small phenocryst of black-elongated amphibole was hardly defined on alphanetic groundmass of sample **KC-01**. Found as fragment from excavated wells with depth of 4m, **KC-05** has exclusively very dark-gray to dark in color and ultrafine groundmass with few white feldsparthoids phenocryst. It can be interpreted that these three samples are within basalt to basaltic andesite composition and they are more likely to suitable for making basalt fiber, due to absence of weathering, alteration and not too high content of silica.

Brittle weathered-basalts layers, exposed at the wall of two excavated wells, shown to be very weak, brittle and highly weathered. Outcrop of sample **KC-03**, as demonstrated above, occurred to have very high mechanical fractures and strongly weathered with clay mineral as evident. In the range of less than 1km apart from **KC-03**, another well expose outcrop of **KC-04,** showing conchoidal fracturing texture at the wall. Physically **KC-04** has less intensity of fracture, higher strength and moderately weathered. These might be the consequence of alteration, causing the two outcrop to be physically and chemically weak to withstand weathering.

With lighter in color, **KC-06**, **KC-07** and **KC-08** exhibits distinct physiochemical characteristics from the two previous groups. Greenish andesitic basalt outcrop, **KC-06**, was found as large blocks exposing from the earth surface and shown to be very hard with high intensity of parallel silicified-fracturing system. **KC-07**, on the other hand, was seen on the ground as vesicular boulder, but its color tends to be deviated from intermediate to below felsic composition. Yellowish secondary minerals were found infilled in pores of the rock sample, indicating present of alteration and weathering. Having similar characteristics to **KC-06**, sample **KC-08** has greenish color and unaltered, but significant intensity of inclusion was observed. White quartz and zeolite like mineral with size from micro to macro scale can been seen by naked eyes on the **KC-08**.

Layered platy-like rock was found in certain area in Khok Chareon as shown as **KC-09** in Figure 4-3. This group of rock exhibits very confusing characteristics to basaltic rocks. It occurs as 30° NW dipping and 10° strike with parallel laminated layers (10-20 cm thickness), but no sedimentary texture is noticeable on the rock surface. Meanwhile color and texture of the rock alike to basaltic rock. It was found underlying the porphyritic vesicular basalt boulders **KC-10** which has calc-plagioclase as phenocryst. It can be interpreted that the underlain layer **KC-09** is metamorphic rock (slate) which was sedimentary rock for before the closing of inter-basin of Indosinia and Shan-Thai plate. Then get covered by basaltic lava during Cenozoic magmatism in Lopburi during post suturing continental rifting as discussed in geology of basaltic rocks of literature review. However, this is just the conclusion from field investigation and petrography should be conducted to clarify.

4.1.2. Chai Badan tenement

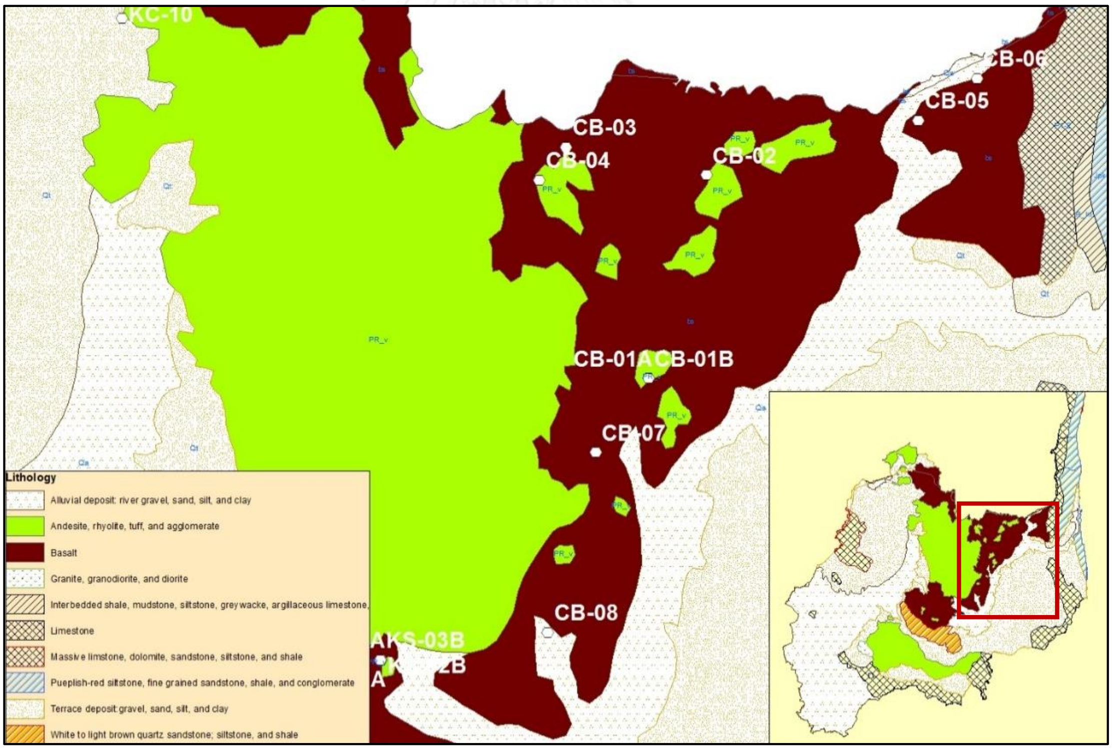


Figure 4-4: Map showing basalt terrain, sampling points and outcrops in Chai Badan

Basaltic rocks in Chai Badan were mapped as discontinuous terrain, within which series of rhyolite bodies are found interrupted at some parts. It was bounded by Quaternary sediments at the eastern part, rhyolitic tuff at the western and limestone at the northeastern part. Lithology of Chai Badan occurred to be more varied than Khok Chareon. As have discussed in geological review, multiple sequences of magmatism with different composition were clearly mapped in this tenement. The rhyolitic bodies found as small plugs within Chai Badan basaltic terrain might have resulted from basaltic lava flooding over older rhyolitic tuff. Chemical alteration was observed by color changes, formation of secondary minerals and weaken physical strength of the rock in the area. Vesicular basalt with high porosity, felsic pyroclastic, platy-like rock, unaltered basalt, chemically and mechanically weathered basalt were found in different areas within the tenement. These occurrences are the indicators of strong lithological and geochemical variation. (see Figure 4-4)

Had been sampled at the overlapping site between rhyolitic tuff and basalt terrain as shown in Figure 4-4 & 4-5, **CB-02** was found along the creek at the toe of rhyolitic mountain. Floats of basalt to andesite were exposed as boulders with diameter between 10-50 cm. The boulder was observed as slightly weathered basalt with non-vesicular and porphyritic texture. With phenocryst of elongated calc-plagioclase and pyroxene, the surface of rock boulder was shown to be very rough due to presence of pores, seemingly as vesicular basalt. This may have been resulted from dissolution by acidic rain of calc-plagioclase and biotite which might have been formed under alteration and recrystallization process while basaltic lava flooded over the rhyolitic basement.

CB-03A and **CB-03B** were found in non-soil area where boulders and fragments, with size from several centimeters to half meter, have shown to be under strong in-situ mechanical weathering. These two samples share the same outcrop, but seemingly having been developed with different processes. With dark-pink color, the **CB-03A** can be regarded as very-fine-grain and vesicular basalt with non-acid-reactive mineral inclusion, doubt to be quartz. On the other hand, with no inclusion, dark-gray **CB-03B** has much higher pore intensity. These vesicular basalts do share common physical properties which can be described as very firm, hard and unaltered.

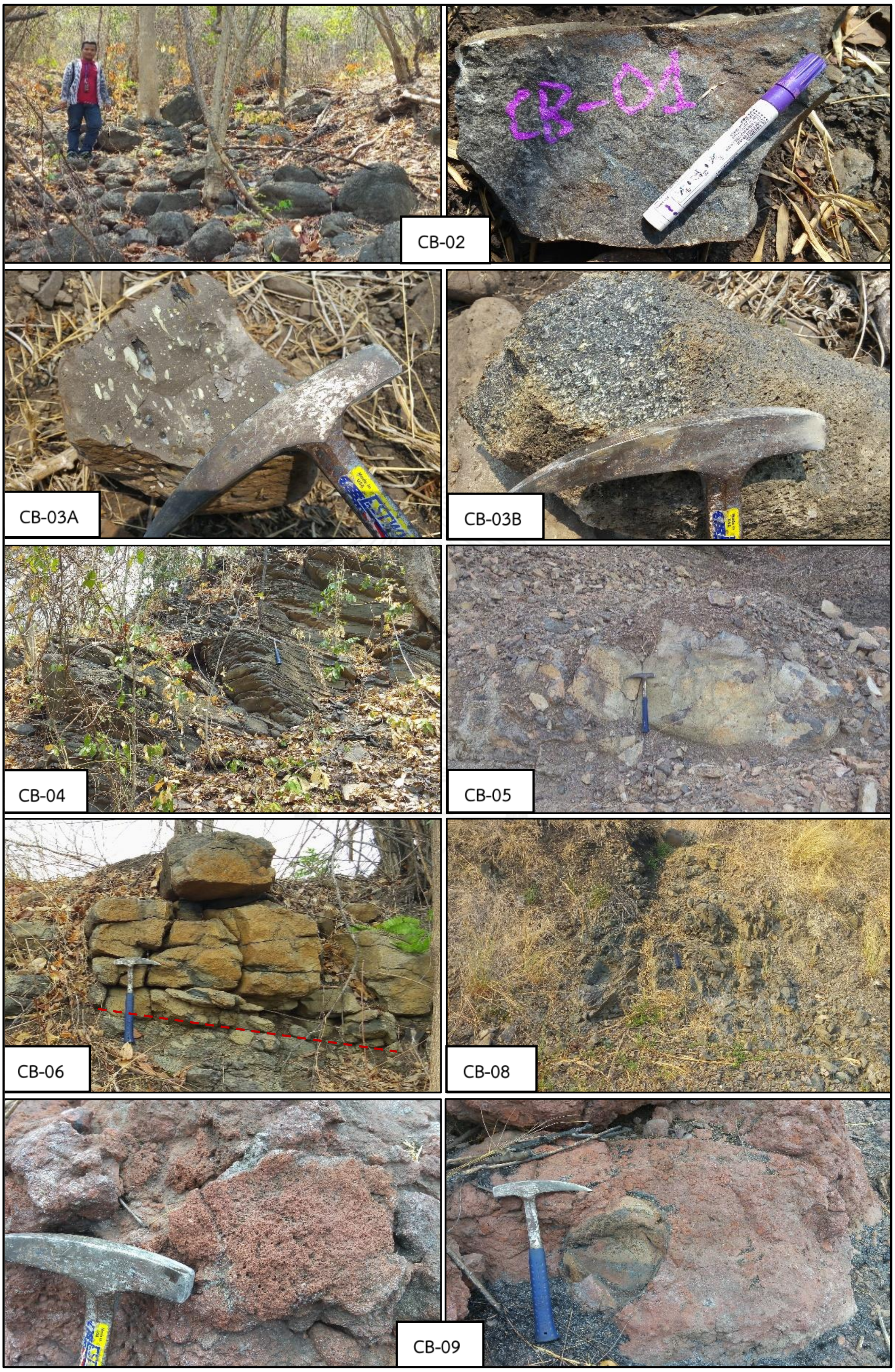


Figure 4-5: Basalt samples and outcrops in Chai Badan tenement

Unlike platy-like basalt in Khok Chareon, which is overlain by vesicular basalt boulders, **CB-04** outcrop exposes on the mountain top with absence of basaltic boulder. Beside laminated layering structure, Chai Badan platy-like rock doesn't show any noticeable sedimentary texture. On the other hand, it has very fine-grained texture with basalt-like color. These platy rock was called as platy basalt by some author, yet it's more likely not basalt. From chemical analysis, high content of silicon oxide was determined, reflecting non-basaltic genesis.

CB-05 and **CB-06** were sampled several kilometers from each other at the northeastern part of Chai Badan. Exposed in 2m depth of excavated well, **CB-05** can be described as fresh, unaltered, firm basalt with aphanitic texture and dark-gray in color. **CB-06** outcrop exhibits as two different layers (see Figure 4-5) with distinct physical properties. The upper layer, with thickness of 20 cm, is mechanically fractured in vertical and horizontal direction, but physically it remains hard and frim. Meanwhile, the lower layer has shown to be chemically weathered. This could be indicator of existence multiple basaltic layers with different chemical composition, allowing them to have different ability to withstand weathering.

CB-08 represents another genesis of basaltic rock in Chai Badan. Having lighter color, it exhibits variation from other rock above but it observed to cover largest part of the tenement. Physically **CB-08** group was found to be very brittle and moderately weak, reflected from present of small fragments and progressing conchoidal fracturing. Chemical alteration might be the main cause of weakening the rock and destroy its phial strength as well as ability to withstand weathering.

As a distinguish lithological feature of Chai Badan, reddish pyroclastic rock, (**CB-09**) was found approximately 500m apart from **CB-04** outcrop. Basalt fragments and boulders were found as clasts, included in the mass. Having red color and very high proportion of quartz crystal, this pyroclastic rock might be felsic series magma with very high iron content. Scoria texture was also observed on the surface of the rock mass (see Figure 4-5 & 4-6). Present of basalt boulder as lenticular structure in the pyroclastic mass indicates that basalt was already weathered prior to the iron-rich felsic blast, which must have been erupted recently.

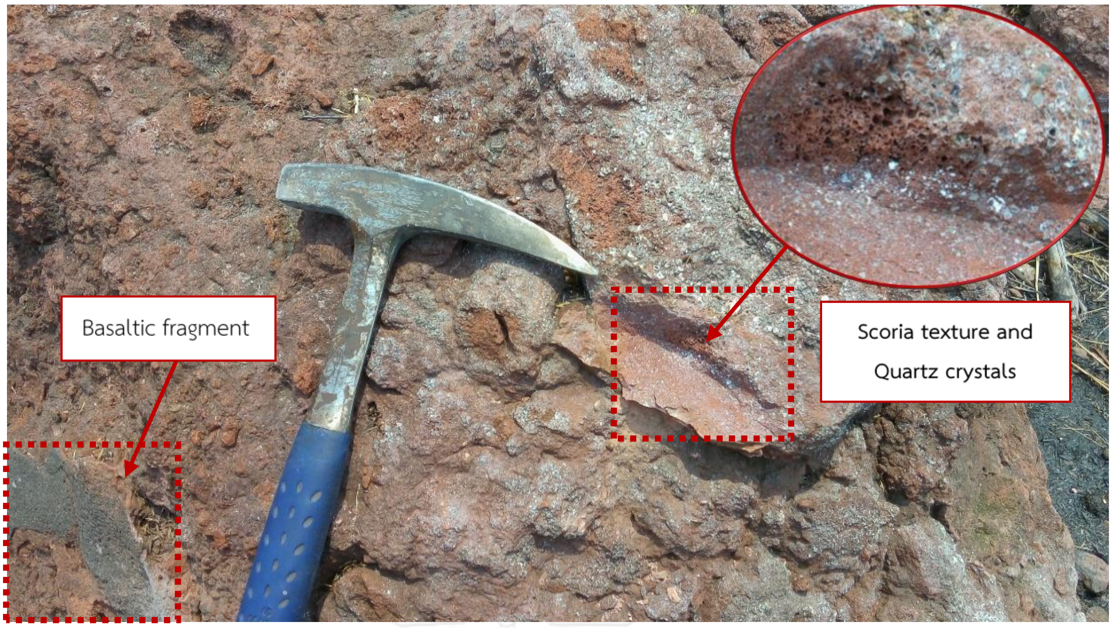


Figure 4-6: Texture of reddish pyroclastic in Chai Badan

4.1.3. Khok Samrong tenement

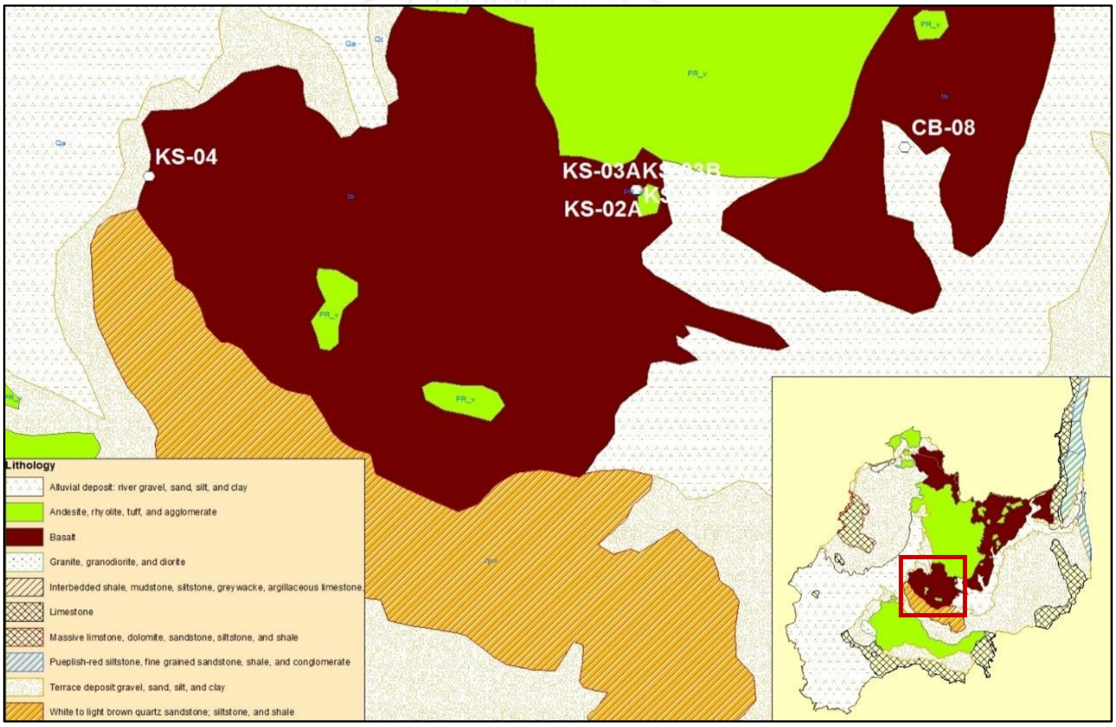


Figure 4-7: Map showing basalt terrain, sampling and outcrops point in Khok Samrong

Khok Samrong tenement is located in the central part of Lopburi Province and is bounded by rhyolitic tuff in the northern part, Quaternary sediments in the northeastern and southwestern part, and sedimentary rocks laying at the southwestern part. Khok Samrong tenement laterally share almost the same geology with Chai Badan for having certain rhyolitic bodies within the basaltic terrain, but less variation was observed. Fresh basalt, platy-like rock, dacite to rhyolite and weathered basalts are seen across the area during field investigation

Figure 4-8: Rock samples in Khok Samrong tenement

Within an aggregate quarry area (Minechem) in Khok Samrong tenement, several lithology variations were discovered. Blackish vesicular basalt (**KS-01**) with alphanetic texture was found moderately weathered and its pore was infilled by secondary yellowish sulfur-bearing mineral. Mechanically **KS-01** is moderately hard but very brittle. At the meantime, **KS-02A** and **KS-02B** exposed at the highly fractured pit's wall, reflecting very weak and brittle mechanical properties (see Figure 4-7 & 4-8).

Situated next to rhyolitic mountain, as shown in Figure 4-7, the chance of having contact-alteration is increased. Regarding to their color, the presence of secondary minerals (oxidized iron-bearing minerals and clay minerals) and weakened-physical strength, these two samples might have been affected by alteration and followed by weathering. Platy-like rocks was also found in the quarry with almost the same properties and characteristics as in Khok Chareon and Chai Badan tenement. Unlike in Chai Badan, where platy-like rock are found on the mountain top, **KS-3A** was dug from the pit as underlain layer similar to the occurrence in Khok Chareon. At the base of rhyolitic mountain, located several hundred meters from the pit, weathered boulders of dacite to rhyolite was found and sampled as **KS-03B**. This rock is very similar to the less weathered **KC-07** in Khok Samrong. In contrast, very fresh non-vesicular basalt (**KS-04**) with ultrafine grain texture was also found.

Result from geological investigation of the three tenement of the study areas provide enough evidence to conclude that the area has a complex geological variation, which has been developed through complicate tectono-magmatic activities during continental suturing and rifting process. Series of inter-sequence volcanism with different composition in Cenozoic has caused contact metamorphism and alteration between rhyolitic and basaltic rock in certain area. Platy-like rock, which is so confusing with basalt, might be a good evidence of regional metamorphism. Commonly occurred, weak and brittle basalts with presence of secondary and clay minerals are indicators of widespread alteration in many areas, especially in Chai Badan. Getting altered, these rocks have changed in chemical and mineral composition, causing them vulnerable to weathering. Even though, degree of weathering has been observed to be varied from high to low, accordingly to distances from rhyolitic rock. However, nature of calc-alkaline basalt itself also is responsible for getting weathered. On the other hand, fresh and unaltered basalt has been found in certain area within the three tenement. Commonly these fresh rocks are found in excavated wells for irrigation purposed at depth varied from 2-4 meters. They usually occur to be very dark-gray to black in color and ultrafine grain texture with uncommon phenocryst. Despite, slightly weathered basalt also found as float boulders with vesicular to non-vesicular texture. Both fresh and slightly weathered basalt are prospective for making basalt fiber.

From geological and physical property standpoint, Khok Chareon was investigated to have higher potential since the area has fewer chemical alteration and weathering comparing to the other two tenements. With less variation it makes ease for controlling production quality. The next priority should be the Khok Samrong and Chai Badan is the last to consider. However, these three tenements do have basalt resources, good for making basalt fiber. It's likely that Khok Samrong and Chai Badan might give less reserve. Though, prioritizing these tenements for commercial application should depend other criteria such as chemical suitability, production scale and other economic factors. Small production scale might be better to choose Khok Samrong Chai Badan. This recommendation is not necessarily to be followed, since disputes on land use was not considered in this study.

4.2. Geochemistry data representation and analysis

4.2.1. Data representation

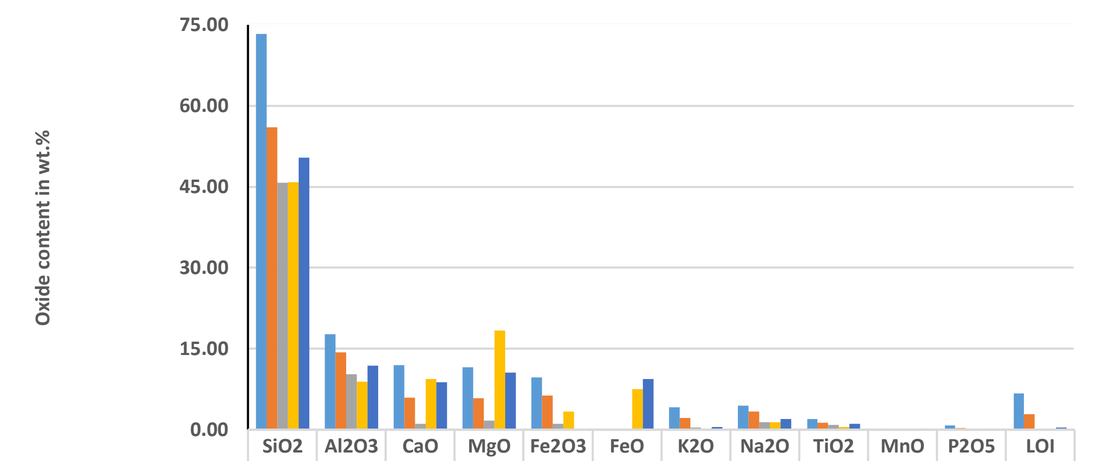
Table 4-1 is the results of X-Ray Fluorescence analysis of basalt samples from Lopburi Province, together with reference data from previous study on suitability of basalt resources for making fiber in Russia, conducted by Pisciotta et al. (2015) and Morozov et al. (2001). Major oxides namely SiO_2, Al_2O_3, CaO, MgO, Fe_2O_3, FeO, K_2O, N_2O, TiO_2, MnO, P_2O_5 are defined as weight percentage (Wt.%). Modulus of viscosity and acidity are expressed in this table as $\mathbf{M_v}$ and $\mathbf{M_a}$, respectively.

Those above results can be presented statistically in Figure 4-9. Lopburi basalts, in average, contain slightly higher weight percentage of SiO_2, Al_2O_3, K_2O and Na_2O and correspondingly lower weight percentage of CaO, MgO, and FeO+Fe_2O_3. Meanwhile, the minimum concentration of major oxides of Lopburi shown closely related to

Melanocratic basalt of Pisciotta et al. (2015). Extremely high SiO_2 and Al_2O_3 was also observed from the population.

Table 4-1: Major oxides of Lopburi basalts obtained from XRF analysis (wt.%), and modulus of viscosity and acidity (Mv and Ma)

Name	SiO_2	Al_2O_3	CaO	MgO	Fe_2O_3	FeO	K_2O	Na_2O	TiO_2	MnO	P_2O_5	LOI	M_a	M_v
KS-01	52.52	11.18	3.02	10.01	3.02	-	4.15	3.5	-	-	-	6.56	4.89	2.8
KS-02A	52.33	11.84	2.74	10.64	2.74	-	3.88	2.33	-	-	-	6.69	4.8	3.03
KS-02B	62.93	10.73	2.86	8.34	2.86	-	3.84	2.34	-	-	-	2.03	6.58	3.66
KS-03A	65.67	11.29	2.34	7.09	2.34	-	2.9	1.4	-	-	-	3.47	8.16	4.79
KS-03B	73.34	10.25	1.11	5.32	1.11	-	3.11	1.75	-	-	-	2.54	13	6.95
CB-01A	55.62	11.21	5.94	9.76	5.94	-	3.42	1.98	-	-	-	1.85	4.26	2.37
CB-01B	54.04	11.71	5.86	11.53	5.86	-	3.01	1.87	-	-	-	1.83	3.78	2.28
LBS-01	45.76	15.82	11.97	6.86	8.91	-	0.4	2.61	1.32	0.14	0.21	5.04	3.27	1.95
LBS-02	51.28	17.67	7.81	4.43	8.89	-	1.53	4.26	1.58	0.14	0.45	1.65	5.63	2.42
LBS-03	57.91	16.42	5.76	3.92	6.24	-	1.88	4.06	1.18	0.12	0.38	1.61	7.68	3.23
LBS-04	49.98	15.61	8.83	6.68	8.76	-	1.23	3.32	1.27	0.13	0.33	3.17	4.23	2.16
LBS-05	62.04	16.77	5.56	1.66	5.17	-	2.17	4.34	0.85	0.05	0.28	0.1	10.92	3.97
LBS-06	51.79	15.4	5.4	2.46	8.64	-	1.51	4.46	2	0.13	0.77	6.06	8.55	2.65
LBS-07	51.25	16.65	8.8	6.25	8.54	-	1.47	3.56	1.23	0.12	0.31	2.27	4.51	2.28
LBS-08	51.91	16.19	8.75	5.81	8.4	-	1.2	3.71	1.39	0.13	0.26	1.06	4.68	2.32
LBS-09	59.34	17.47	5.32	2.89	6.4	-	2.34	4.31	1.15	0.1	0.39	1.14	9.36	3.41
LBS-10	59.12	17	5.77	1.89	5.66	-	1.94	4.13	1.07	0.06	0.36	1.96	9.94	3.72
LBS-11	49.77	15.77	8.79	6.02	9.03	-	0.95	3.68	1.45	0.14	0.28	2.21	4.43	2.17
LBS-12	60.51	13.31	4.64	2.78	6.12	-	2.79	4.29	1.14	0.09	0.38	1.06	9.95	3.26
LAN-01	54.23	15.41	6.1	4.28	9.73	-	1.07	4.46	1.16	0.17	0.18	4.47	6.71	2.4
LAG-01	55.78	13.94	7.25	3.31	8.79	-	0.96	3.45	0.85	0.16	0.19	3.09	6.6	2.57
Melanocratic Basalt	45.83	8.92	9.34	18.35	3.39	7.48	0.09	1.43	0.52	0.2	0	0	1.98	1.46
Andesitic Basalt	49.92	15.96	10.52	8.22	2.8	6.44	0.64	2.21	0.68	0.13	0	0	3.52	2.43
Calc-Alkaline	47.29	16.85	10.39	6.5	9.87	0	0.96	3.61	0.61	0	0	0	3.8	1.97
Myandukha Basalt	50.42	11.82	8.84	10.58	-	9.43	0.52	2	1.04	0.18	0.21	0.42	3.2	2.36
Kondopoga Basalt	53.54	14.12	6.6	6.7	-	7.64	1.04	3.8	1.52	0.2	0.22	0.32	5.09	3.17
Berestovetskoe	49.03	12.58	9.93	5.47	-	10.15	0.66	2.34	2.85	0.32	0.21	0.96	4	2.6
Marneul'skoe	50.61	16.75	9.07	4.65	-	3.6	1	3.88	1.81	0.18	0.24	0.55	4.91	3.79



	SiO2	Al2O3	CaO	MgO	Fe2O3	FeO	K2O	Na2O	TiO2	MnO	P2O5	LOI
Max	73.34	17.67	11.97	11.53	9.73	0.00	4.15	4.46	2.00	0.17	0.77	6.69
Mean	56.05	14.36	5.93	5.81	6.34	0.00	2.18	3.32	1.26	0.12	0.34	2.85
Min	45.76	10.25	1.11	1.66	1.11	0.00	0.40	1.40	0.85	0.05	0.18	0.10
Melanocratic Basalt	45.83	8.92	9.34	18.35	3.39	7.48	0.09	1.43	0.52	0.2	0	0
Myandukha Basalt	50.42	11.82	8.84	10.58	0	9.43	0.52	2	1.04	0.18	0.21	0.42

Figure 4-9: Diagram showing summarized statistic of major oxides of Lopburi basalts, Melanocratic and Myandukha basalt.

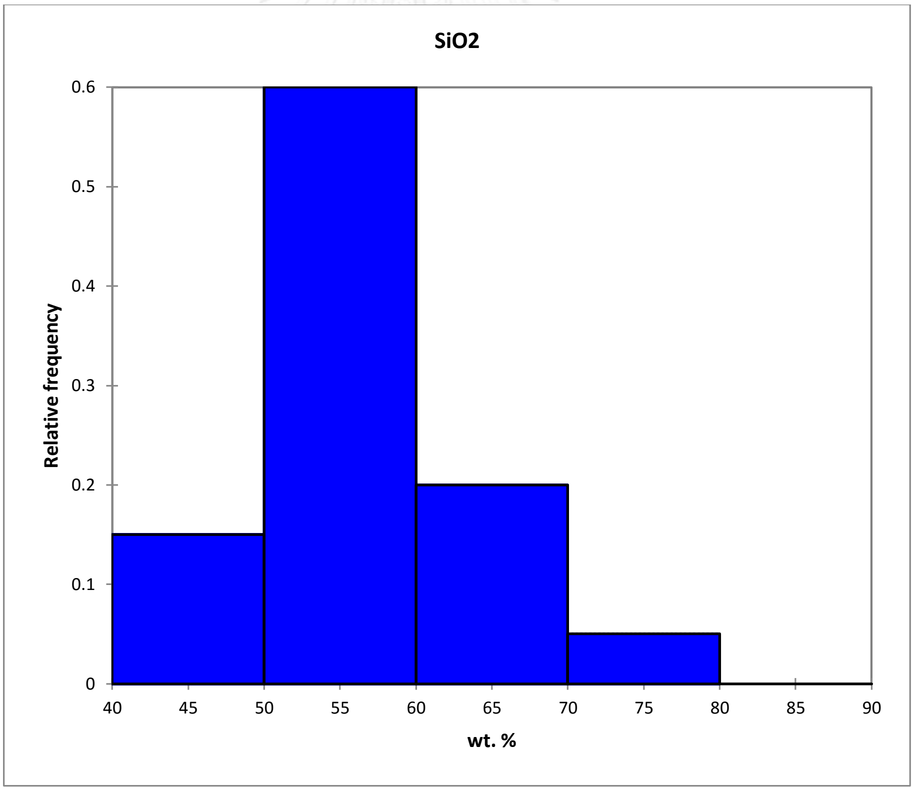


Figure 4-10: Histogram of SiO_2 concentration in wt.%

Figure 4-10 shows that Lopburi basalts have concentration of SiO_2 as the following: [40-50] wt.% =25%, [50-60 wt.%] = 15% and [60-80 wt.%] =25% of the population. This demonstrate that the majority Lopburi basalt has higher silica concentration than Melanocratic basalt and within good range comparing to samples of Morozov.

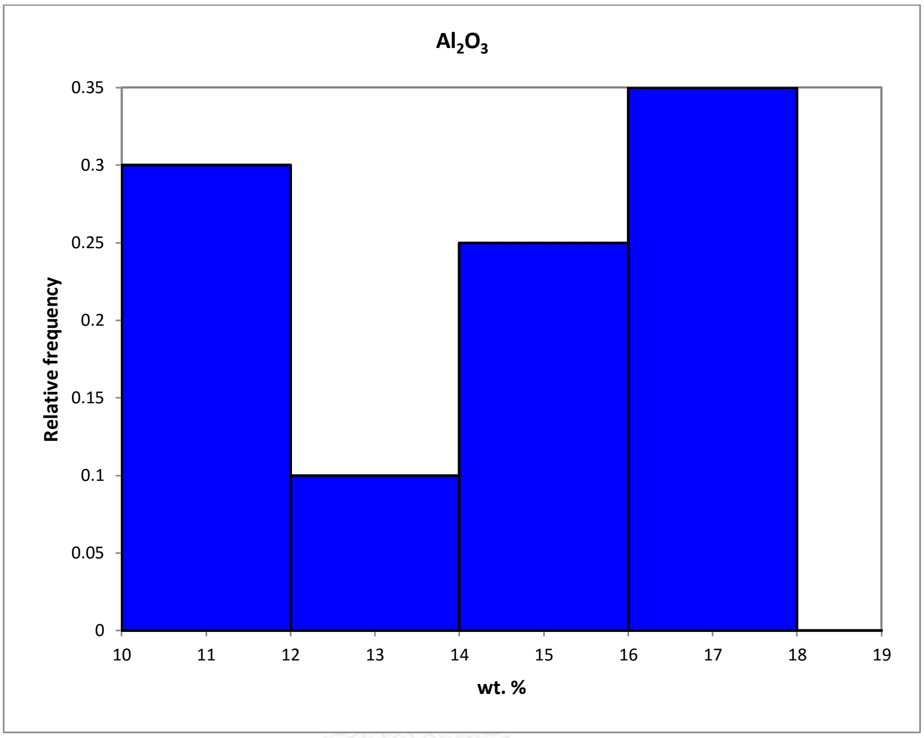


Figure 4-11: Histogram of Al_2O_3 concentration in wt.%

Figure 4-11 illustrates that Lopburi basalts have concentration of Al_2O_3 as the following: [10-12 wt.%] = 30%, [12-16 wt.%] = 35% and [16-18 wt.%] =35%. This indicates that alumina concentration of basalts in Lopburi evenly spread between 10 wt.% - 18 wt.%. However, the majority of the samples tend to contain moderately high Al_2O_3 (14-18 wt.%) = 60% of the population. Good range of Al_2O_3 according to the reference samples is within [12-15 wt.%]. However, effects of Al_2O_3 is collectively considered with SiO_2, expressed as SiO_2+Al_2O_3 (acidity).

CaO concentration exhibits normal distribution with maximum of 11.97 wt.% and minimum of 1.11 wt.%. Histogram as shown in Figure 4-12 depicts that 70% of Lopburi samples has concentration within [5-10 wt.%], 25% within [1.11-5 wt. %] and 5% within [10-11.97 wt.%]. The distribution of CaO indicates that the majority of Lopburi basalt contain lower CaO than samples of both Pisciotta and Morozov. Having low content of CaO is a sign of having low basic, which is represented by CaO+MgO (basic). Since the basic value is low, the possibility of having high acidity modulus is increased.

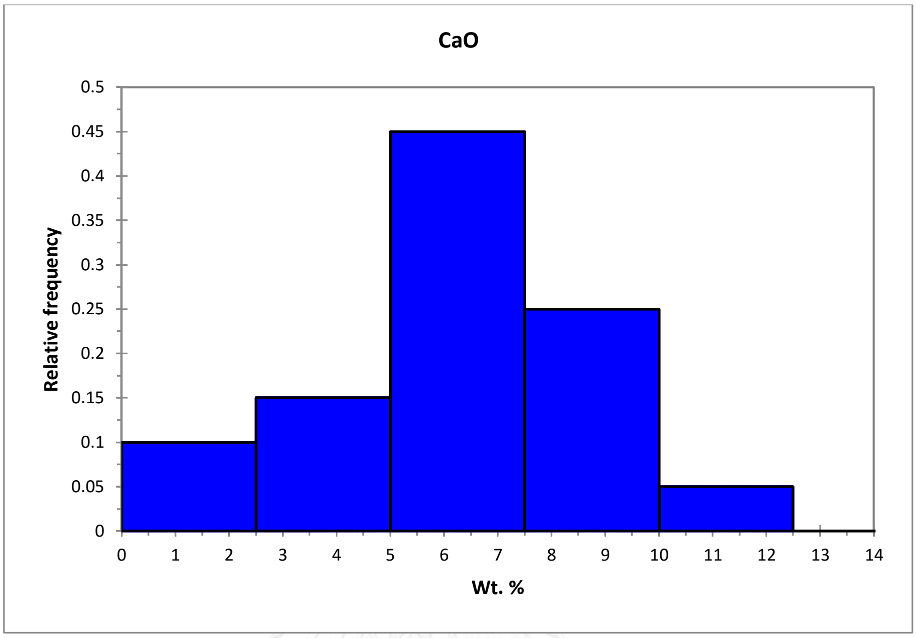


Figure 4-12: Histogram of CaO concentration in wt. %

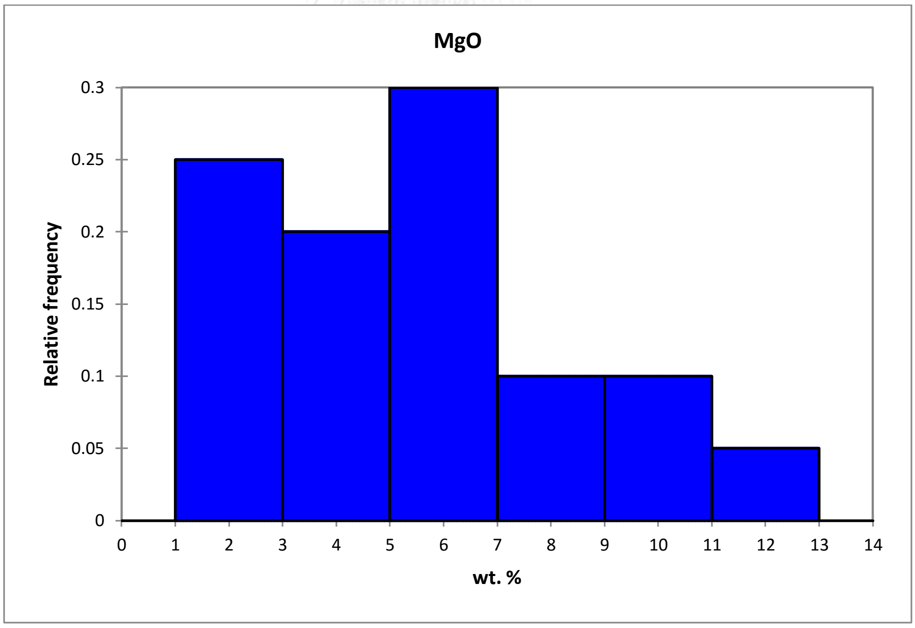


Figure 4-13: Histogram of MgO concentration in wt.%

Between 1 wt.% to 5 wt.%, MgO concentration of Lopburi basalt represent 45% of the samples, and other 40% are within 5 wt.% to 9 wt. %. The rest 5% of samples contain more than 9 wt. %, but less than 13 wt.%. Due to the MgO distribution, Lopburi basalts can be clearly divided into three groups: 1. low MgO wt.%, corresponding to high viscosity and acidity; 2. medium MgO wt. %, corresponding to slightly lower viscosity and acidity; and 3. high MgO wt.% corresponding to low viscosity and acidity. As MgO has collective impacts to viscosity and acidity, CaO+MgO wt.% (acidity) is the factor to be considered in grouping these samples. (see Figure 4-13)

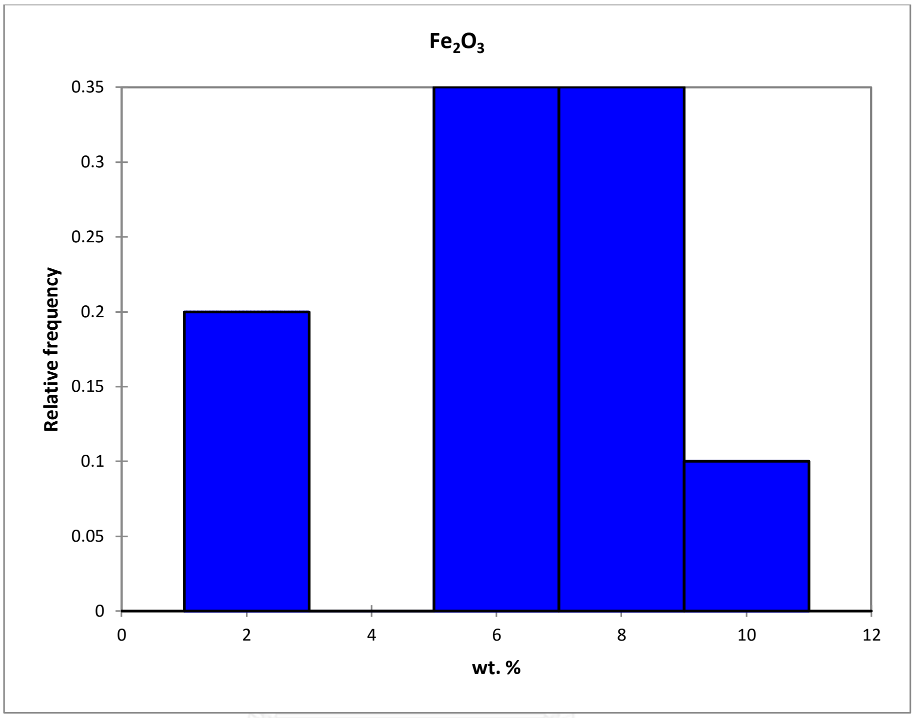


Figure 4-14: Histogram of Fe_2O_3 concentration in wt.%

Iron content, expressed as Fe_2O_3, is one of the most important oxides to be considered. Recrystallization ability of molten basalt is increasing with high content of iron in natural rock. Lopburi basalts as shown in Figure 4-14 contain Fe_2O_3 less than 12%, which could be regarded as a good concentration range for making basalt fiber. However, the histogram did show two distinct groups of basalt in terms of iron content: [1-3 wt.%] and [5-11] wt.% with relative frequency 20% and 80% respectively. The very low Fe_2O_3 batch requires attention, since it could negatively impact viscosity and acidity.

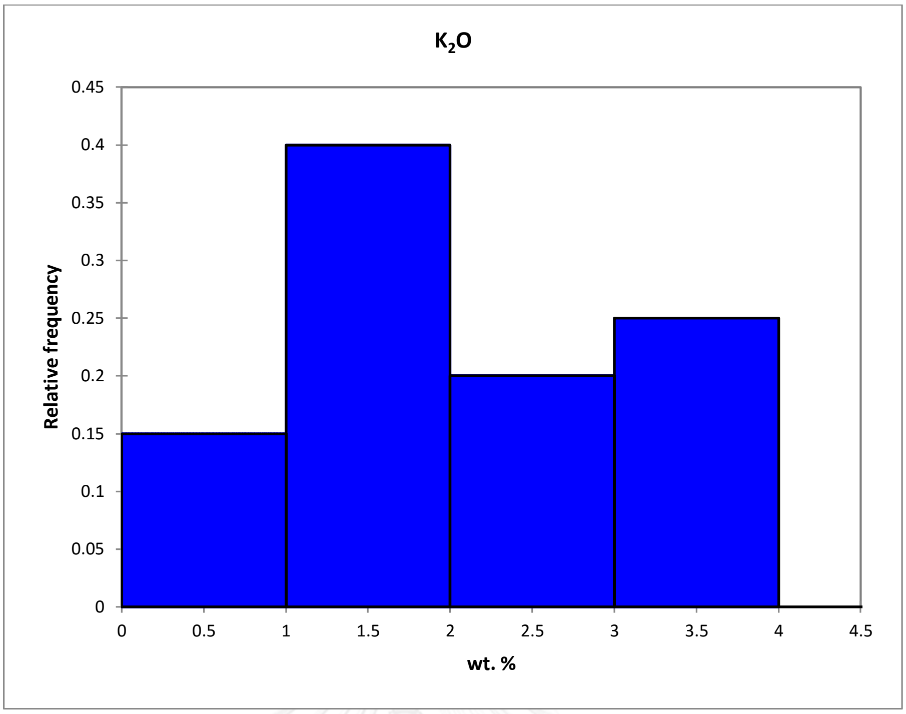


Figure 4-15: Histogram of K_2O concentration in wt.%

Three groups of samples can be classified according to histogram, as demonstrated in Figure 4-15: low-K basalt group, which has K_2O wt.% within 0.09 wt.% to 1 wt. %, represents 15% of the population; K-rich basalt, containing K_2O wt.% between 1wt.% to 3 wt.%, takes 60% of the total number of observation; And very-high-K basalt, with K_2O wt.% concentration from 3 wt.% to 4 wt.%, shares 25% of the total number of observation. Comparing to samples of Pisciotta et al. (2015) and Morozov et al. (2001), the majority of Lopburi basalts contain considerably higher concentration of K_2O.

Following almost the same behavior with K_2O, the concentration of Na_2O, as shown in Figure 4-16, could be grouped into three classes: 1. relatively low-Na basalt, containing Na_2O within [1-2] wt.%, represents 20% of total number of samples; 2. Na-rich basalt, having Na_2O concentration from 2 wt.% to 4 wt.%, takes 45%; and 3. high-Na basalt, with Na_2O wt.% greater than 4 wt.% and less than 5 wt.%, comprises 40% of the total number of samples. All Lopburi basalts contain higher concentration of Na_2O than all samples of Pisciotta and almost all of samples of Morozov. This indicates that basaltic rocks of Lopburi province has significant high Na_2O concentration.

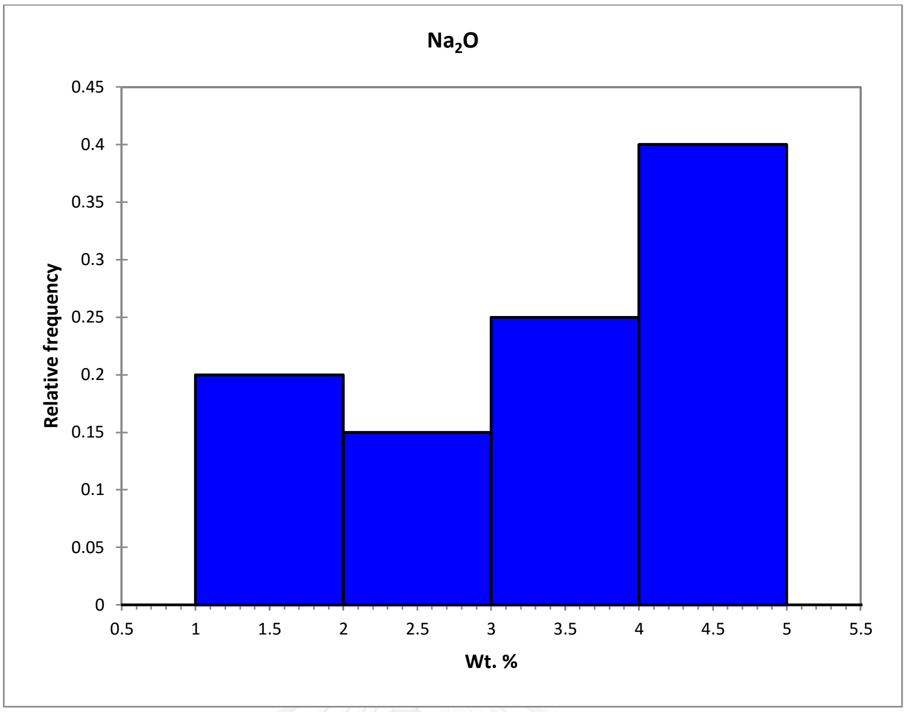


Figure 4-16: Histogram of Na_2O concentration in wt. %

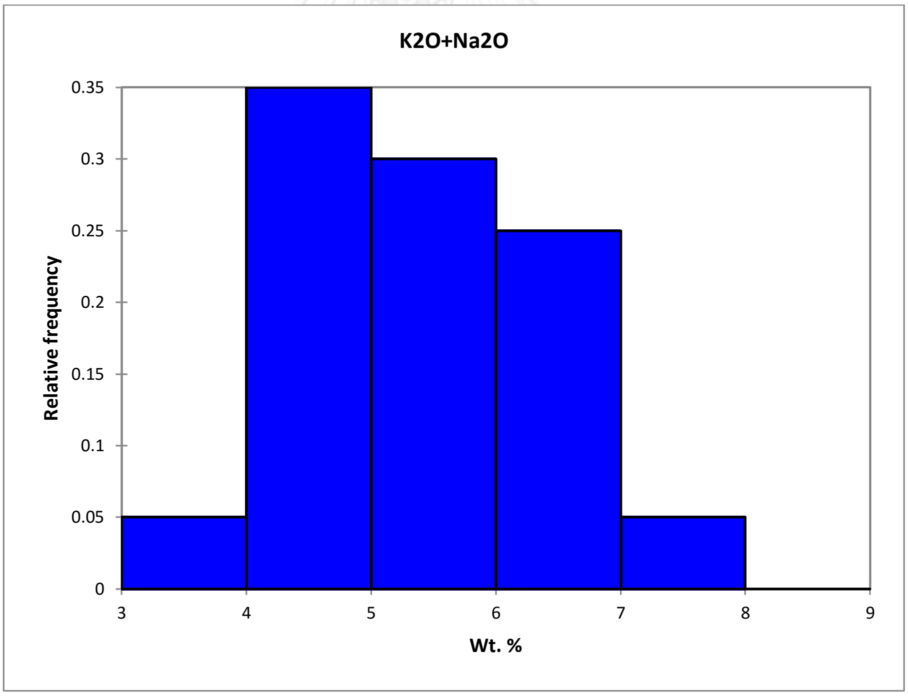


Figure 4-17: Histogram of total-alkali concentration, (K_2O+Na_2O) wt.%

Noticeably weight percentage of both K_2O and Na_2O of Lopburi basalts shown to be higher than samples of [8, 9]. Total alkalis (K_2O+Na_2O) has reverse impacts with SiO_2+Al_2O_3 (acidity) to viscosity and acidity. The majority Lopburi basalts, as shown above, contain relatively high SiO_2 and Al_2O_3, which is a sing of having high viscosity and acidity. On the other hand, according to [8, 9], high alkalinity help to reduce viscosity and acidity.

4.2.2. Variation analysis

Harker variation diagrams (Figure 4-18) shows variation of major oxides (Al_2O_3, CaO, MgO, Fe_2O_3+FeO, K_2O, Na_2O, TiO_2 and MnO) against SiO_2. These diagrams are plotted major oxides from Lopburi basalt and samples of [8, 9] for comparison purposes. These Harker diagrams demonstrate that TiO_2, MnO, CaO and Fe_2O_3+FeO have stronger relationship with SiO_2 than Al_2O_3, MgO, K_2O and Na_2O.

Although the trend line shows that Al_2O_3 decreases, accordingly to the increasing concentration of SiO_2, but the deviation of linear relationship of samples is very high. Below SiO_2 = 57.50 wt.%, two groups of samples were observed: 1. Al_2O_3 = [10-13 wt.%] which is grouping with Myandukha and Berestovetskoe basalt of [9] and 2. Al_2O_3 = [14.24-18] wt.% which shows strong relationship with Marneul'skeo basalt of [9] as well as Andesitic basalt and calc-alkaline basalt of [8]. Above SiO_2 = 57.50 wt.%, Lopburi basalts also are distributed into two groups, low and high **Al**, but they do not exhibit any relationship with reference samples. From the variation diagram of Al_2O_3, we can interpret that, within appropriate SiO_2 wt.% range, Lopburi basalts are comprised of two groups: high and low **Al**, which corresponds to higher or lower viscosity and acidity groups. (see Figure 4-18)

SiO_2 – CaO variation diagram shown to be negatively decreasing with lower deviation than SiO_2-Al_2O_3. Most of the CaO concentration of Lopburi basalts are observed to be lower than all samples of [8, 9] and moderately decrease with the increasing of SiO_2 concentration. However, a set of Lopburi basalts is observed to have relationship with Kondopoga basalt of [9], which is a good candidate for making CBF since it has higher $\mathbf{M_v}$ and $\mathbf{M_a}$. Meanwhile another set shows in relation with other three sample of [9] and Andesitic basalt of [8], which can be used as single material for drawing staple fibers since it could be homogenously molten at 1450 ^{o}C, crediting its low viscosity. (see Figure 4-18)

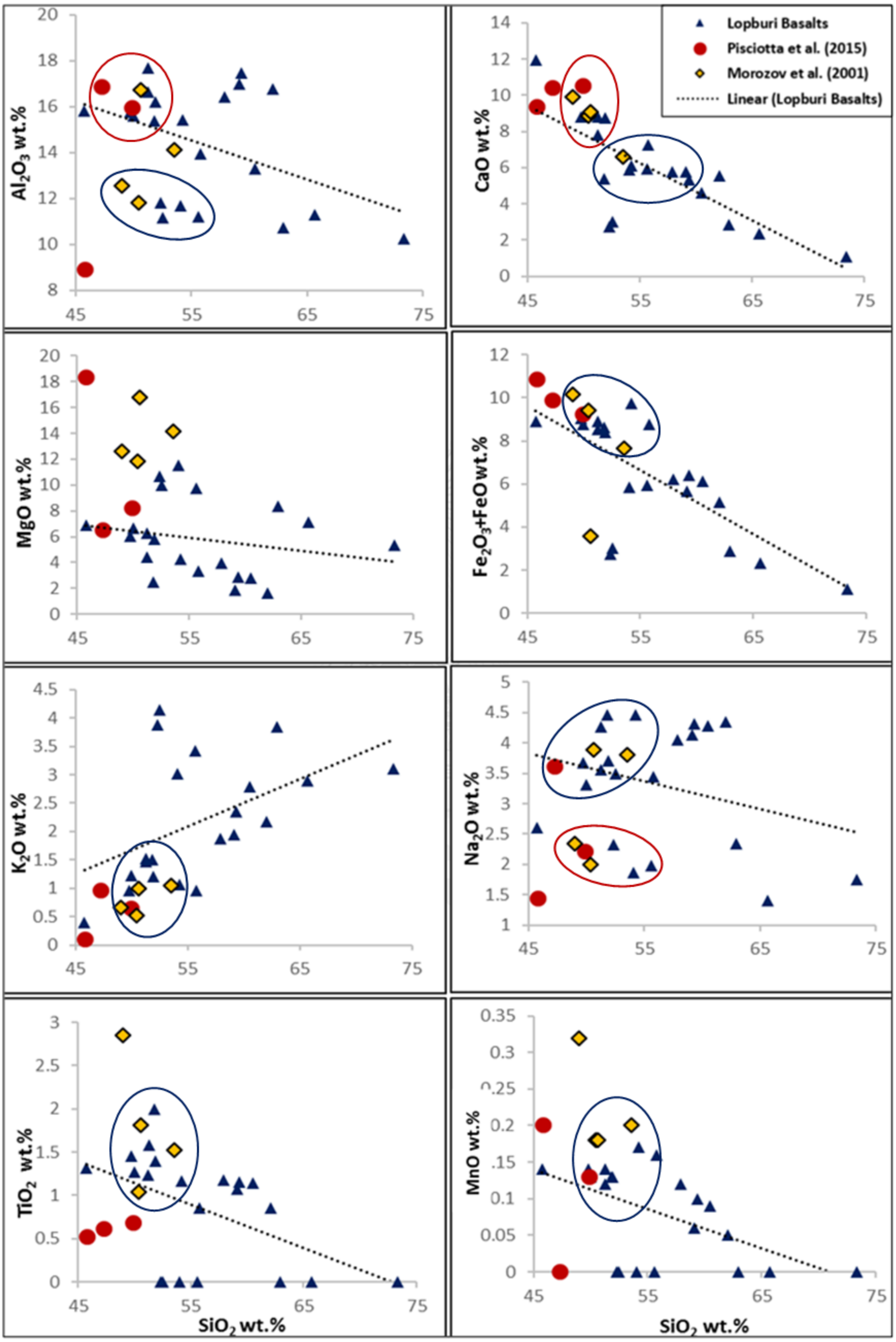


Figure 4-18: Harker variation diagrams of major oxides

SiO_2 - MgO variation diagram demonstrates even poorer linear relation than CaO, its basic companion. MgO wt.% of Lopburi basalts shown to split into two groups, below and above the trend line. These two groups have negative relationship with SiO_2, since the MgO wt.% is steadily decreased with the increasing of SiO_2. As observed, concentration of MgO of Lopburi basalts are lower than all samples of [9] and Melanocratic basalt of [8]. This indicates that basalts from Lopburi could have lower basic. (see Figure 4-18)

Total iron content expressed as Fe_2O_3 + FeO has almost the same variation with CaO. With the increasing of SiO_2 wt.%, the total iron content decrease moderately. Some of Lopburi basalts appear as group with Andesitic Basalt and calc-Alkaline Basalt of [8] as well as Myandukha Basalt, Kondopoga Basalt and Berestovetskoe of [9]. This group contain total iron content from 7.50 wt.% to 11 wt.% with SiO_2 concentration between 47 wt.% to 56 wt.%, which is considered to be suitable range of both oxides. Meanwhile, above 56 wt.%, **Fe** is depleting dramatically, signaling very high viscosity and acidity trend.

SiO_2 - K_2O and SiO_2 - Na_2O variation diagrams show contrast trending, since **K** appears to be increased with the increasing concertation of **Si** while **Na** follow contrarily direction. However, their linear deviations are both very high, reflecting low relationship between samples. For K_2O one grouping was observed. Except Melanocratic basalt, other sample of both [8, 9] are grouped with a set of Lopburi basalts in SiO_2 – K_2O variation diagram. This group contain very low concentration of **K**, where K_2O wt.% is in between 0.5 wt.% and 1.50 wt.% and SiO_2 wt.% = [47-55 wt.%]. However, within 47 wt.% <SiO_2 wt.%<56 wt.%, some basaltic rocks of Lopburi has very high **K**, where K_2O wt.% = [2.80-4.50 wt.%] and it appears in slightly increasing trend with SiO_2. This help to reduce melting temperature and viscosity with no impacts to fiber strength. On the other hand, Na_2O exhibit worse linear relation with too big deviation, which can be conclude that N_2O of Lopburi basalt doesn't have any variation relationship with SiO_2. Na_2O wt.% appear as two portions, 0 wt.% < Na_2O wt.% < 3 wt.% and 5 wt.% > Na_2O wt.% > 3 wt.%. The majority of the samples are shown to have Na_2O wt.% greater than 3 wt.% and less than 5 wt.%. For Na_2O, two grouping were observed (Figure 4-18). With Na_2O wt.% < 3 wt.%, a group of Lopburi basalts appear as group with Myandukha and Berestovetskoe basalt of [9] and Andesitic basalt of [8]. Meanwhile, another big group with Na_2O wt.% > 3 wt.% follows Kondopoga and Marneul'skoe basalt. Because the decreasing variation of Na_2O is deviated and most of the samples has high Na_2O concentration, the collective impact of alkalinity (total alkalis = K_2O+Na_2O) follow the increasing trend of SiO_2 - K_2O variation. The high alkalinity property could help to reduce viscosity and melting temperature of high SiO_2 + Al_2O_3 rocks.

Since XRF Analytical results of some samples doesn't provide TiO_2 and MnO, the variation diagrams of these two oxides with SiO_2 isn't completed, but it does indicate that these two element has decreasing trend with increasing SiO_2 wt.%.

4.2.3. Total Alkali-Silica Classification (TAS)

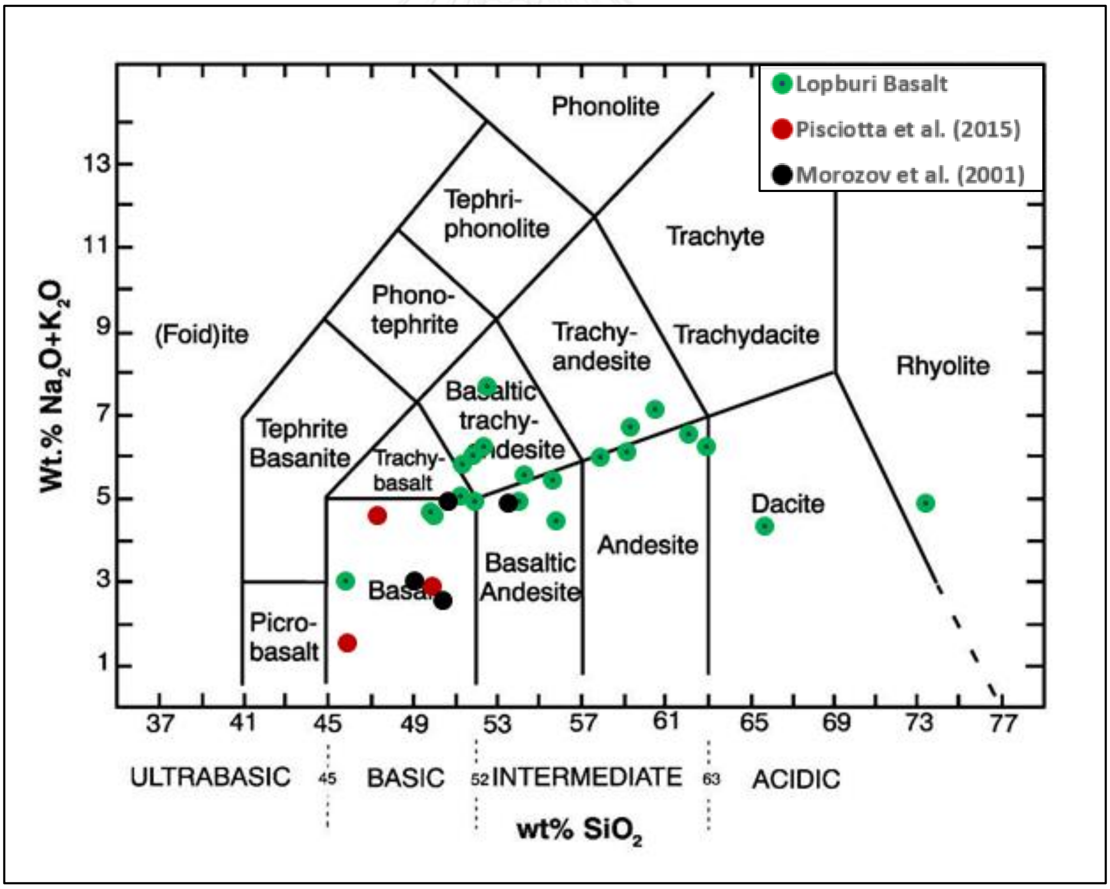


Figure 4-19: Total alkali-silica (TAS) classification diagram of Lopburi basalts, basalt samples of Pisciotta and Morozov, after [33]

From TAS classification diagram as shown in Figure 4-19, lithology of rocks in Lopburi extends from basalt, andesitic basalt, basaltic-trachy andesite, andesite, trachy andesite, dacite and rhyolite. Very few samples from the study area are fallen into basalt type, the majority of them are basaltic andesite, basaltic-trachy andesite, trachy andesite and andesite, while two others have composition of dacite and rhyolite. The variability of rock sub-types in the study area strongly related to discrete sequences of magmatism as discussed in geology part. Weight percentages of silica and total alkalis has shown to be increasing, making basaltic rock in the area move away from basic to acidic composition, and from andesitic to trachy series. Basalt samples of [9], all shown to be basalt to basaltic andesite, while samples of [8] are in basalt sub-type.

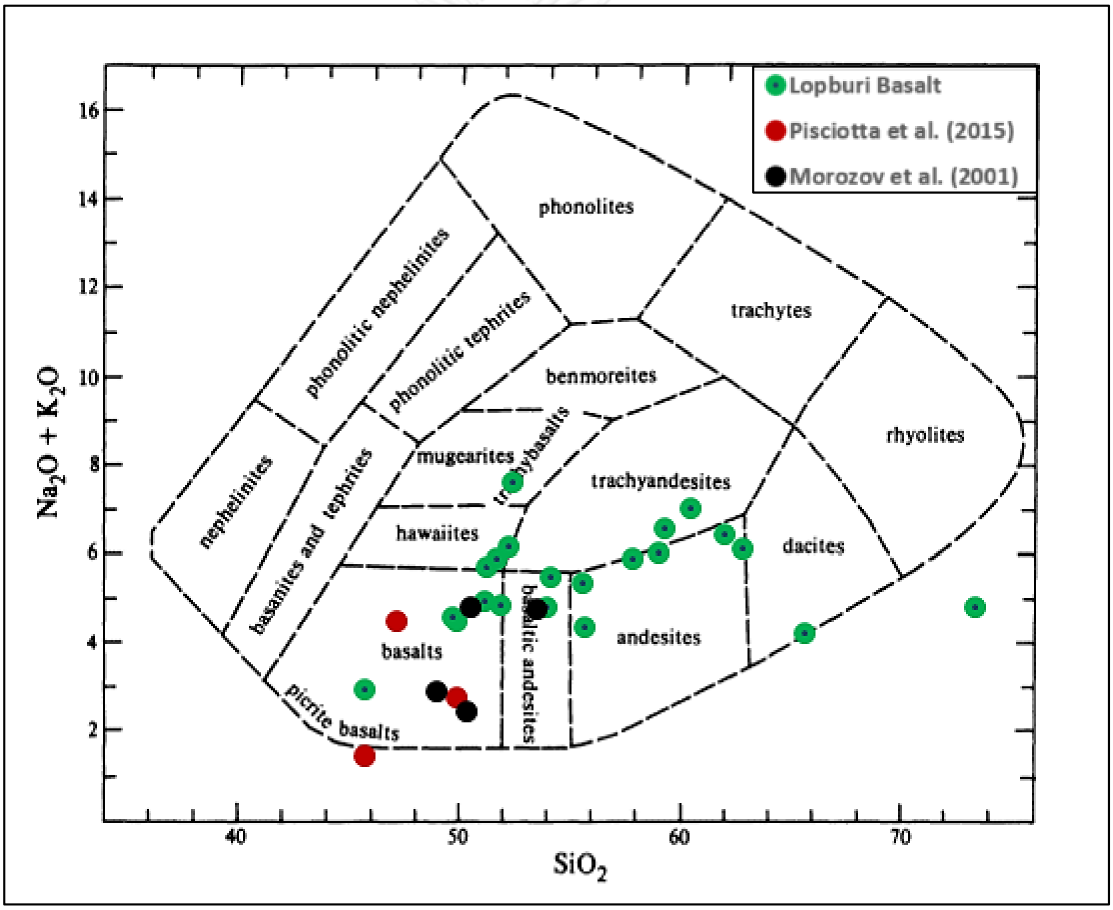


Figure 4-20: Total alkali-silica (TAS) classification diagram of Lopburi basalts, basalt samples of Pisciotta and Morozov, after [34]

Another TAS classification diagram (Figure 4-20) developed by [34] is a nomenclature diagram of volcanic rocks. Two samples, Melanocratic basalt and one sample from Lopburi appear out of the classification range. Melanocratic basalt, which is concluded by [8] as unsuitable basalt rock for making high quality fiber, contain very low total alkalinity and it is followed by only one basalt sample from Lopburi, with SiO_2 wt.% < 46 wt.%. Meanwhile, one of Lopburi sample contain extremely high SiO_2 wt.% with relatively low concentration of total alkalis and it stay out of nomenclature range of Cox et al. (1979). The TAS nomenclature diagram above demonstrates that rocks with concentration of: SiO_2 = [46-52] wt.% and Total alkalis = [2-6] wt.% are **Basalts**; SiO_2 = [51-53] wt.% and Total alkalis = [5-9] wt.% are **Hawaiities** and **Trachybasalt**; SiO_2 = [54-57.5] wt.% and Total alkalis = [4-6] wt.% are **Basaltic Andesites**; SiO_2 = [57.5 – 63] wt.% and Total alkalis = [4-7] wt.% are **Andesites** and **Trachyandesites** and SiO_2 > 63 wt.% is dacite.

Lopburi basalt could be classified into two major groups, basalt-basaltic andesite and andesite. Samples of [8, 9] are within basalt-basaltic andesite group, followed by many Lopburi rocks. This indicates that a reasonable number of Lopburi samples are comparable to those of Morozov et al. [9].

4.2.4. Magmatic series classification

From magma series classification diagram (K_2O-SiO_2) demonstrated in Figure 4-21, two-third samples from Lopburi, together with samples of [9] are calc-alkaline series, while the Melanocratic sample of [8] is tholeiitic (low K) series, followed by one of Lopburi sample. Other one-third of Lopburi samples are classified as high K calc-alkaline series and Shoshonitic series. This indicates that Lopburi basaltic rocks are calc-alkaline to high K calc-alkaline series which known to be closely related to continental collision environment. These basaltic rocks contain higher amount of alkalis than other types. There is only one sample from Lopburi basalt shown in relation with Melanocratic basalt, which is not suitable for good quality CBFs, while the considerable amount of samples follows the samples of Morozov, which known to be good for making basalt fiber. Meanwhile high K calc-alkaline and shoshonitic series seem to stay in acceptable SiO_2 wt.% range, but having higher alkalis provides poorer acid resistance fiber.

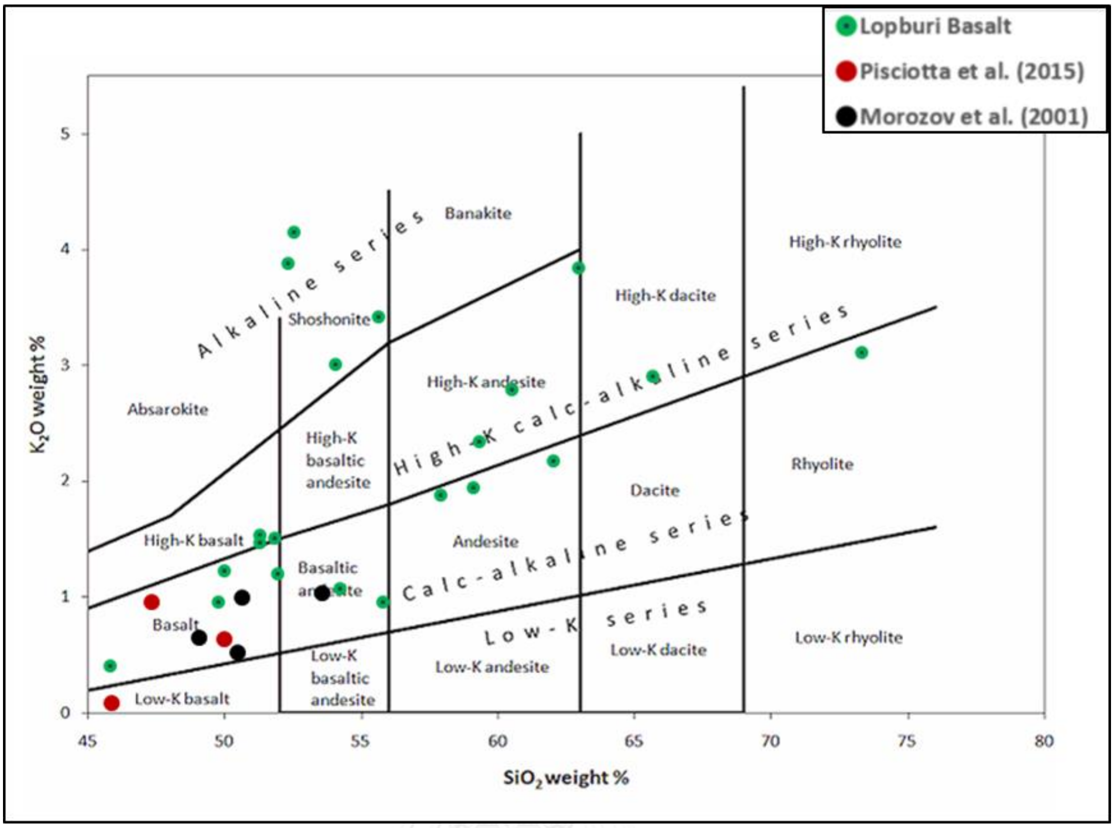


Figure 4-21: Magmatic series classification diagram, after [35]

AFM classification diagram as shown in Figure 4-22 and 4-23 are two other magmatic series classification diagrams. Both diagram provide almost the same results, but their discrimination curves are slightly different. For AFM diagram developed by [6] proves that all of Lopburi rock samples are originated from calc-alkaline magma series, while few samples of both [8, 9] situate above discrimination curve, tholeiitic magma series. Similarly the AFM diagram of [7] classified all Lopburi samples and samples of [8, 9] as calc-alkaline series rock, except the Melanocratic basalt which is classified as tholeiitic series. All though, the two diagram used different discrimination curves, both of these demonstrates rock sample of Lopburi are calc-alkaline series.

Combination of these three magma series classification diagram, it can be concluded that Lopburi basalts are originated from Calc-alkaline magma series, which mostly associated with continental-related basalt. As has been reviewed, Lopburi volcanism activities are developed during suturing of Indosinia and Shan-Thai continental block as well as basin rifting in late Cenozoic. Lopburi basalts are comprised of Calc-alkaline series and high-K Calc-alkaline series. Below SiO_2 = 55 wt.

% quite big number of samples are in relationship with sample of Morozov et al. (2001), which is motivated indicator that some of Lopburi basalts are good for making basalt fiber.

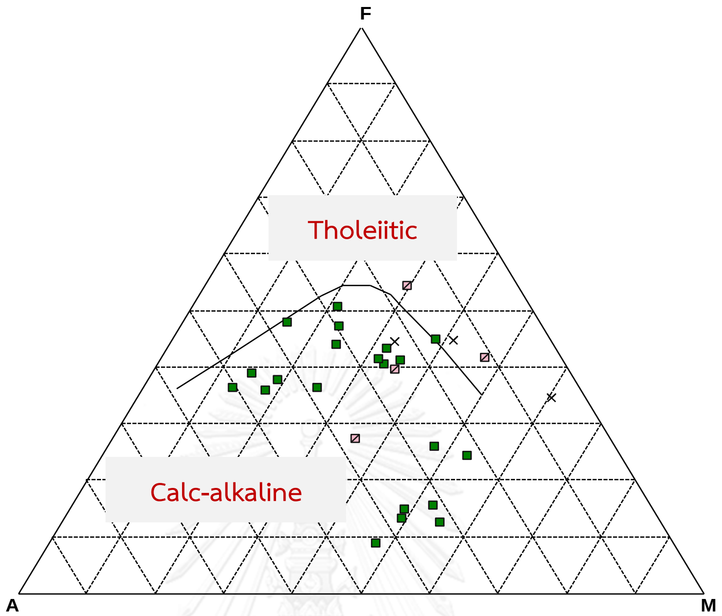


Figure 4-22: AFM magma series classification diagram, after [6]

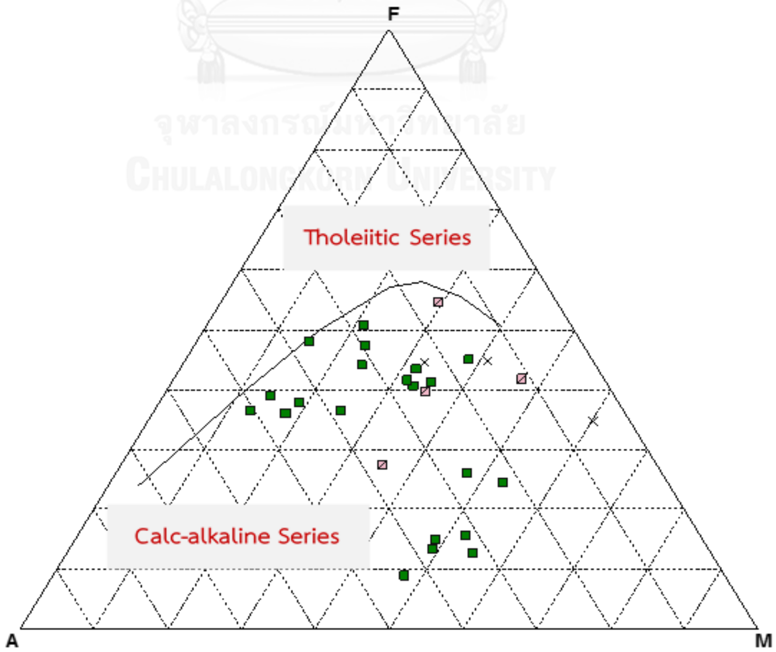


Figure 4-23: AFM magmatic series classification diagram, after [7]

4.2.5. Modulus of viscosity and acidity

Table 4-2 shows result of calculated acidity and viscosity parameters of rocks sample from Lopburi and [8, 9]. These result are calculated according to **Equation 1** formulated by US Paten [10], where SiO_2 +Al_2O_3 ,CaO+MgO, K_2O+Na_2O represents acidity, basic and alkalinity respectively. While Modulus of acidity and viscosity are defined as: Ma = (SiO2+Al2O3)/(CaO+MgO)

Mv = (2Al2O3+SiO2)/(2Fe2O3+FeO+CaO+MgO+K2O+Na2O)

Table 4-2: Showing calculated acidity and viscosity parameters of Lopburi samples and samples of [5, 6].

Samples	A	B	C	D	E	A/B	D/E
	SiO_2+Al_2O_3	CaO+MgO	K_2O+Na_2O	2Al2O3+SiO2	B+C+2Fe_2O_3+FeO	M_a	M_v
KS-01	63.7	13.03	7.65	74.88	26.72	4.89	2.80
KS-02A	64.17	13.38	6.21	76.01	25.07	4.80	3.03
KS-02B	73.66	11.2	6.18	84.39	23.1	6.58	3.65
KS-03A	76.96	9.43	4.3	88.25	18.41	8.16	4.79
KS-03B	83.59	6.43	4.86	93.84	13.51	13	6.95
CB-01A	66.83	15.7	5.4	78.04	32.98	4.26	2.37
CB-01B	65.75	17.39	4.88	77.46	33.99	3.78	2.28
LBS-01	61.58	18.83	3.01	77.4	39.66	3.27	1.95
LBS-02	68.95	12.24	5.79	86.62	35.81	5.63	2.42
LBS-03	74.33	9.68	5.94	90.75	28.1	7.68	3.23
LBS-04	65.59	15.51	4.55	81.2	37.58	4.23	2.16
LBS-05	78.81	7.22	6.51	95.58	24.07	10.92	3.97
LBS-06	67.19	7.86	5.97	82.59	31.11	8.55	2.65
LBS-07	67.9	15.05	5.03	84.55	37.16	4.51	2.28
LBS-08	68.1	14.56	4.91	84.29	36.27	4.68	2.32
LBS-09	76.81	8.21	6.65	94.28	27.66	9.36	3.41
LBS-10	76.12	7.66	6.07	93.12	25.05	9.94	3.72
LBS-11	65.54	14.81	4.63	81.31	37.5	4.43	2.17
LBS-12	73.82	7.42	7.08	87.13	26.74	9.95	3.26
LAN-01	69.64	10.38	5.53	85.05	35.37	6.71	2.40
LAG-01	69.72	10.56	4.41	83.66	32.55	6.60	2.57
Melanocratic Basalt	54.75	27.69	1.52	63.67	43.47	1.98	1.46
Andesitic Basalt	65.88	18.74	2.85	81.84	33.63	3.52	2.43
Calc-Alkaline Basalt	64.14	16.89	4.57	80.99	41.2	3.80	1.97
Myandukha Basalt	62.24	19.42	2.52	74.06	31.37	3.20	2.36
Kondopoga Basalt	67.66	13.3	4.84	81.78	25.78	5.09	3.17
Berestovetskoe	61.61	15.4	3	74.19	28.55	4	2.60
Marneul'skoe	67.36	13.72	4.88	84.11	22.2	4.91	3.79

M_v and M_a of basalt rocks from Lopburi are within [3.52-13] ≥ 3 and [1.95-6.95] ≥ 1.50, respectively. These results clearly indicate that basalt rocks from Lopburi has both M_v and M_a above the Melanocratic basalt and the minimum requirement of US Patent [10].

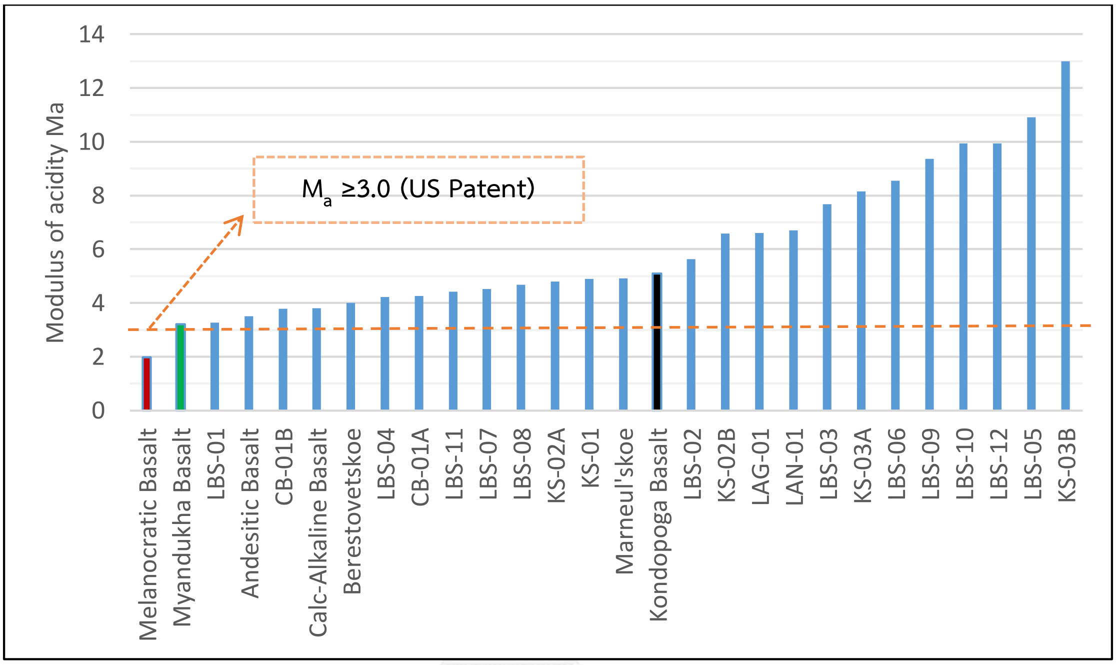


Figure 4-24: Modulus of acidity of Lopburi samples and [8, 9]

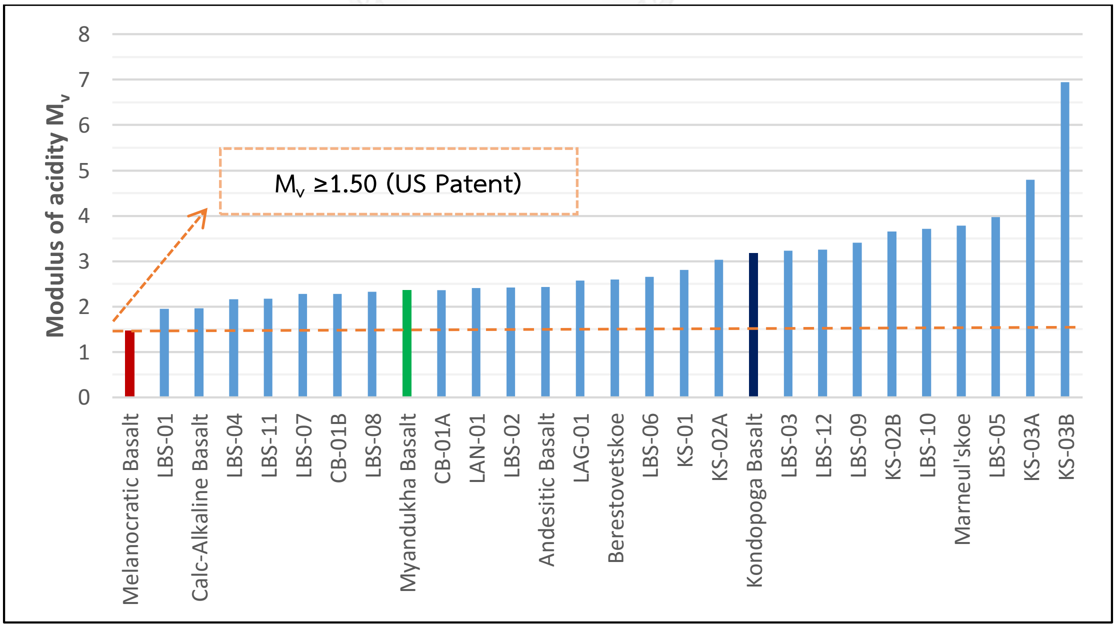


Figure 4-25: Modulus of viscosity of Lopburi samples and [8, 9]

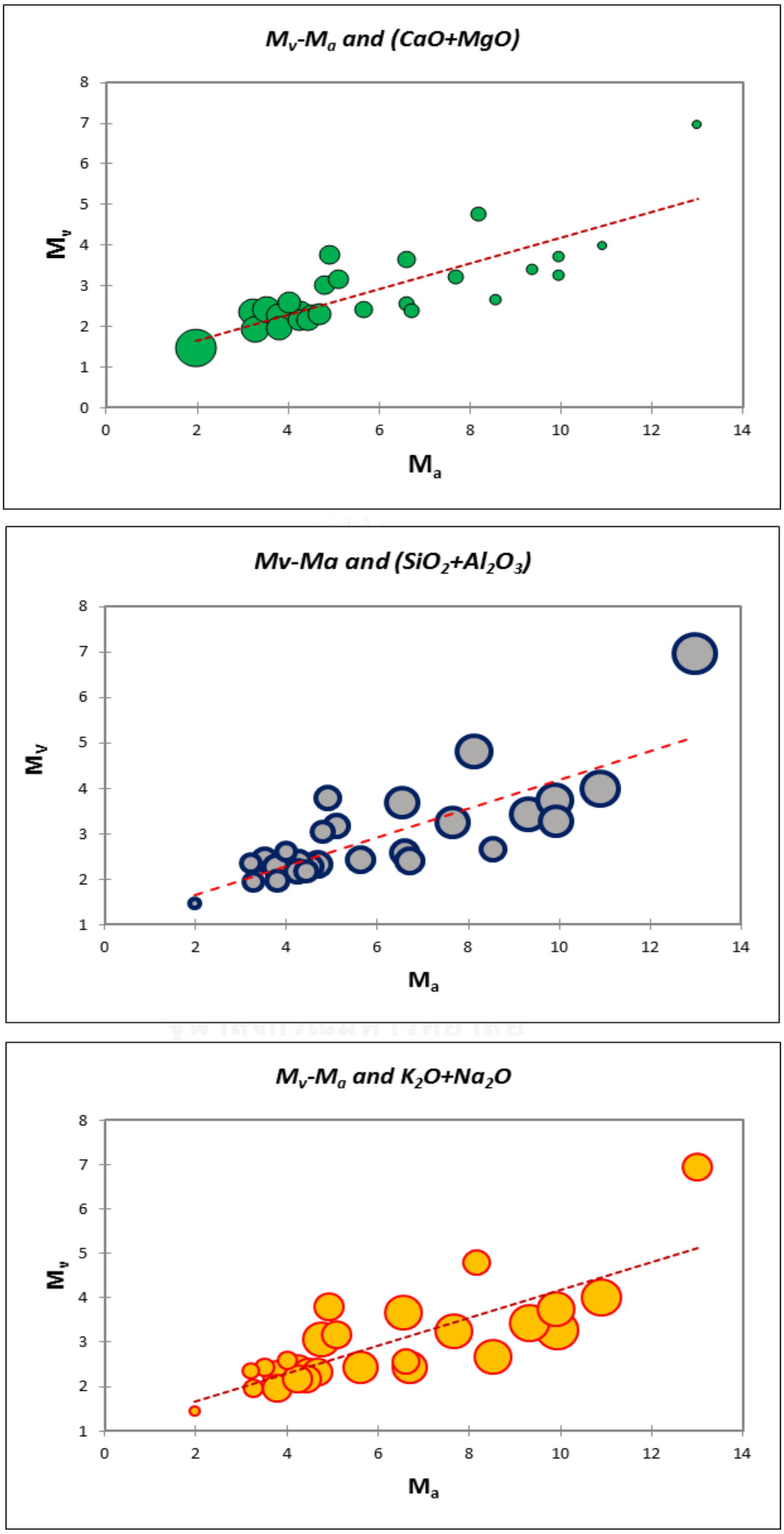


Figure 4-26: 3D Relationship of Modulus of acidity - viscosity and (SiO_2+Al_2O_3), (CaO+MgO) and (K_2O+Na_2O)

Comparing to Myandukha basalt, which has low Modulus of viscosity and acidity and be able to homogeneously melt at 1450 °C, many samples of Lopburi basalts appear to be closely related. Apart from that, many others have not so much different M_a and M_v from Kondopoga basalt, which known to have higher acidity and viscosity than Myandukha basalt and is suitable for producing continues basalt fiber. However, there're also certain amount of samples occurred as having far greater M_a and M_v than Kondopoga basalt, making this group unsuitable to homogeneously melt at commercially applicable temperature.

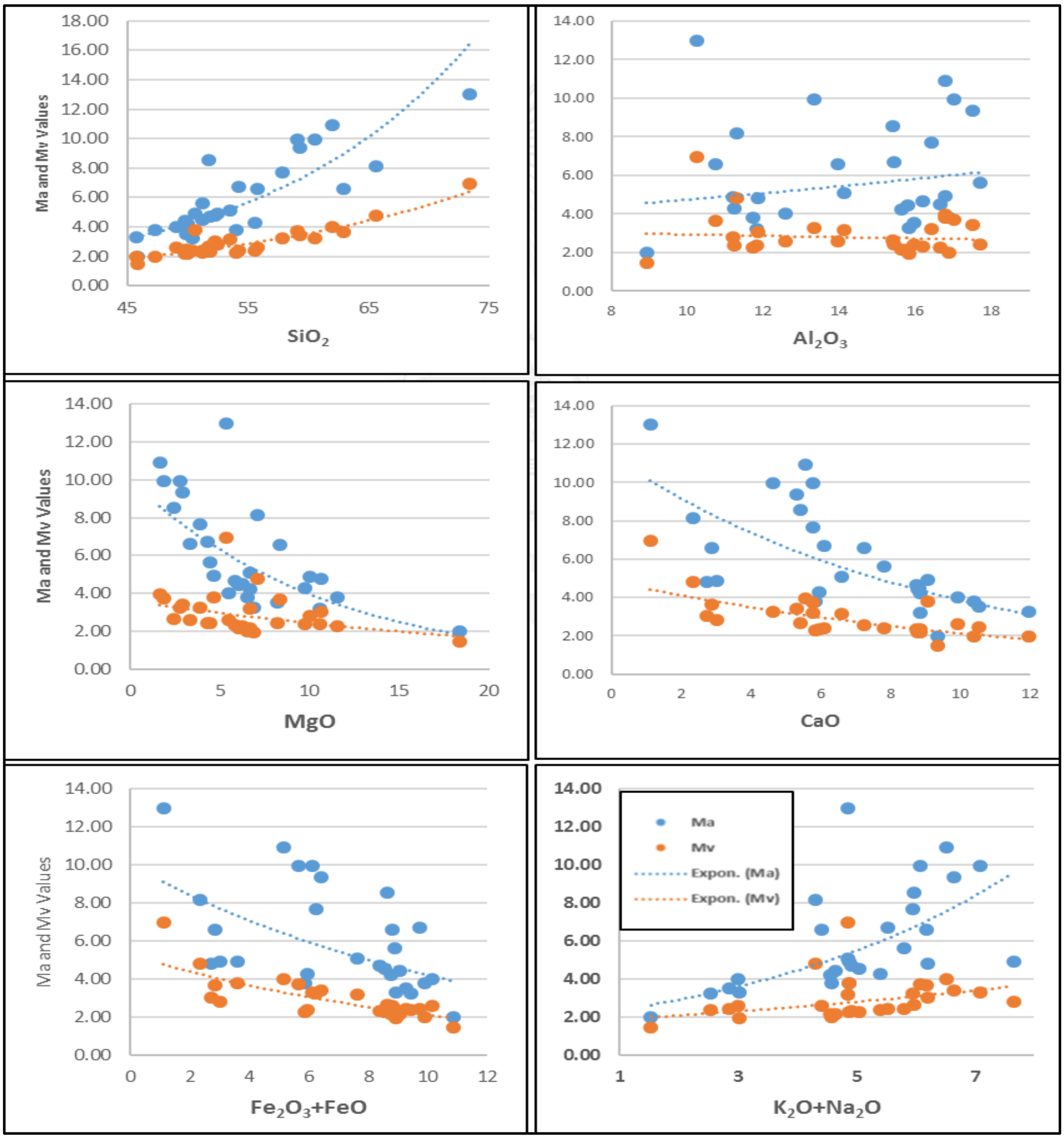


Figure 4-27: 2D relationship between oxides vs. M_v & M_a

Figure 4-26 shows that **M_v** and **M_a** has positive relationship, indicated by steadily increasing trend. Accordingly, (SiO_2+Al_2O_3) appear to have the same trend with the two modulus, as illustrated by increasing the marker size as the two modulus increase. But for (CaO+MgO) exhibits absolute negative trend from the two modulus. On the other hand, Figure 4-27 is indicating 2D relationship of the two modulus with oxides. These graph suggest that **M_v** and **M_a** has very strong and slightly increasing relationship with SiO_2 and alkalinity, respectively. Meanwhile they exhibit from steadily to slightly decreasing relationship with MgO, CaO and total iron content.

4.3. Melting curve analysis

Comapring to Morozov's samples, the average oxides compisition of Lopburi basalt share very good relationship, ranging from rock type, magnatic series, acidity and viscosity modulus. Thus the majority of basalt rocks in Lopburi province are good for making continous basalt fiber. Some samples of Lopburi basalt has lower acidity modulus, but it still better than Melanocratic basalt. In addition, fewer samples contain too high SiO_2 and Al_2O_3, resulting in having too high viscosity. A set of selected basalt samples, as shown in Table 4-3, has weight percentage of almost all oxides within the range of [9] samples and closely related the **B02** (original basalt ore) and **BG01** (modified from **B02** by adding dolomite to reduce melting temperature) used by Apirat (2016).

The viscosity curves below demonstrate that most of basalt sample selected doesn't shown any significant variation to the B02. Most of them has Log[viscosity] in between 1.2 to 2.5 Pa*s within temperature range of 1450 – 1500 ^oC. Meanwhile the dolomite-modified sample, **BG01**, shown to have distinguish pattern and have lower viscosity and melting point, 1.10 Pa*s at 1400 ^oC. This result indicates that raw basalt samples within the chemical composition range selected are suitable for making fiber at commercially applicable temperature. To save melting cost, basalt ore could be modified by using dolomite as had been studied by [36], but the cost of adding to dolomite comparing to melting should be tolerated. Nonetheless, not only the sample selected have potential to produce quality fiber, but also for those with higher range of (SiO_2+Al_2O_3). As discussed in above, the higher range ore could provide better strength, lower crystallization and thermal insulation and also it cost more to produce.

Table 4-3: Selected basalt samples from Lopburi and [36] for melting curve analysis

Samples	SiO2	Al2O3	CaO	MgO	Fe2O3	K2O	Na2O	TiO2	MnO	P2O5
LBS-11	49.77	15.77	8.79	6.02	9.03	0.95	3.68	1.45	0.14	0.28
LBS-04	49.98	15.61	8.83	6.68	8.76	1.23	3.32	1.27	0.13	0.33
LBS-07	51.25	16.65	8.8	6.25	8.54	1.47	3.56	1.23	0.12	0.31
LBS-02	51.28	17.67	7.81	4.43	8.89	1.53	4.26	1.58	0.14	0.45
LBS-06	51.79	15.4	5.4	2.46	8.64	1.51	4.46	2	0.13	0.77
LBS-08	51.91	16.19	8.75	5.81	8.4	1.2	3.71	1.39	0.13	0.26
KS-02A	52.33	11.84	2.736	10.64	2.736	3.875	2.33	-	-	-
KS-01	52.515	11.18	3.021	10.01	3.021	4.15	3.50	-	-	-
CB-01B	54.041	11.71	5.86	11.53	5.86	3.01	1.87	-	-	-
LAN-01	54.23	15.41	6.1	4.28	9.73	1.07	4.46	1.16	0.17	0.18
BG01	48.16	18	12	4	10	2.18	4	1.38	0.18	-
B02	53.31	18.1	8.1	2.3	9.8	2.18	4.55	1.38	0.18	-

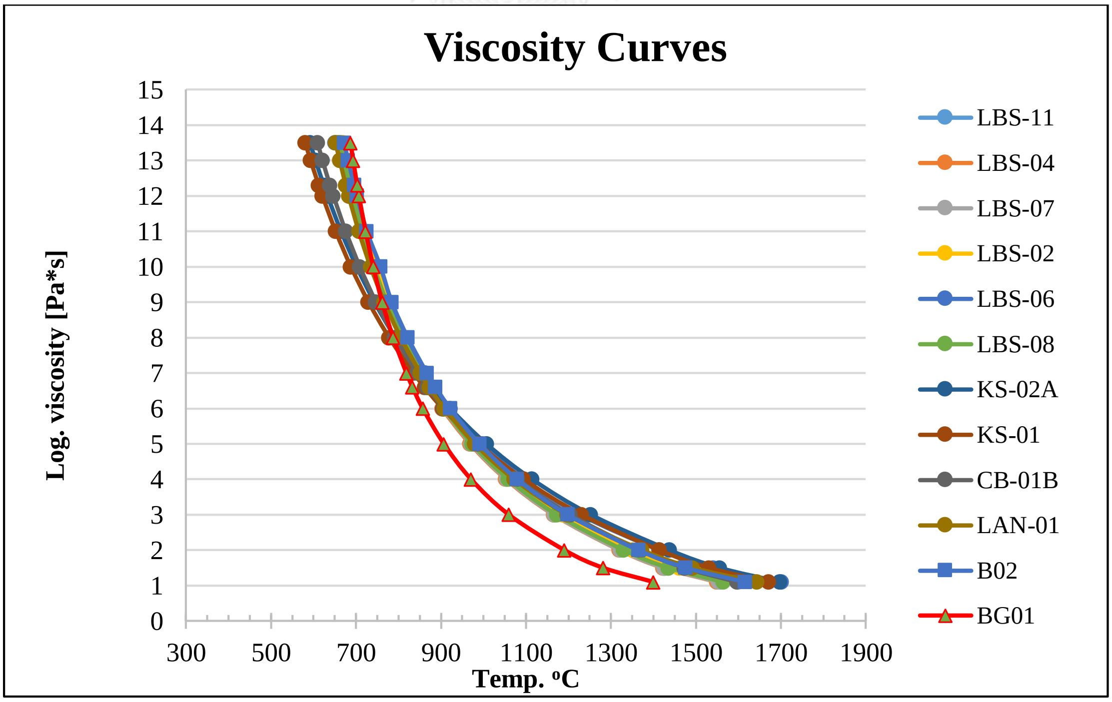


Figure 4-28: Melting curves analysis of selected Lopburi basalt samples and sample of [36], calculated from statistical model developed by www.glassproperties.com

Table 4-4: Statistically calculated Log. viscosity and corresponding temperatures of selected Lopburi basalt samples and samples of Dr. Apirat [36], using excel worksheet developed by www.glassproperties.com

Log. viscosity (Pa*s)	Temp. °C										[36]	
	LAN-01	CB-01B	KS-01	KS-02A	LBS-08	LBS-06	LBS-02	LBS-07	LBS-04	LBS-11	BG01	B02
1.1	1643.1	1597.3	1671.4	1697.6	1564.7	1701.9	1599.6	1553.5	1549.8	1557.0	1399.8	1616.4
1.5	1492.3	1472.4	1530.7	1555.6	1434.8	1541.3	1461.4	1425.0	1422.7	1427.7	1281.2	1476.6
2.0	1373.1	1368.1	1413.8	1437.5	1330.3	1414.5	1351.3	1321.7	1320.2	1323.7	1190.1	1365.1
3.0	1196.5	1203.9	1230.9	1252.5	1172.6	1227.2	1186.9	1166.2	1165.0	1167.0	1059.6	1198.4
4.0	1072.1	1080.4	1094.3	1114.2	1059.2	1095.4	1070.0	1054.5	1053.0	1054.4	970.6	1079.8
5.0	979.6	984.2	988.5	1006.9	973.8	997.7	982.7	970.5	968.8	969.6	906.6	991.0
6.0	908.3	907.2	904.0	921.2	907.1	922.3	914.9	905.0	902.8	903.4	856.9	922.1
6.6	872.7	867.9	861.1	877.6	873.6	884.8	881.1	872.2	869.7	870.3	832.8	887.7
7.0	851.5	844.0	835.0	851.2	853.6	862.4	860.8	852.5	849.7	850.4	818.5	867.1
8.0	805.3	791.4	777.7	792.9	809.7	813.7	816.6	809.5	806.2	806.9	787.4	822.2
9.0	766.9	746.8	729.2	743.7	773.0	773.2	779.8	773.5	769.9	770.6	761.4	784.7
10.0	734.5	708.6	687.7	701.5	742.0	739.1	748.7	743.1	739.0	739.8	740.5	758.1
11.0	706.8	675.4	651.8	664.9	715.3	710.0	722.0	717.0	712.5	713.4	722.4	726.0
12.0	682.9	646.4	620.4	633.0	692.2	684.8	699.0	694.3	689.5	690.5	706.8	702.5
12.3	676.3	638.3	611.7	624.2	685.8	677.9	692.7	688.1	683.2	684.2	702.5	696.1
13.0	662.0	620.7	592.7	604.8	671.9	662.8	678.8	674.5	669.4	670.5	693.2	682.0
13.5	652.5	609.0	580.1	592.0	662.7	650.8	669.7	665.5	660.2	661.3	687.1	672.7

CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS

5.1. Conclusions

Basalt fiber with outstanding properties comparing to ready-available fibers, prospectively becomes future material of choice in fiber reinforcement technologies such as fiber-reinforced concretes, basalt-fiber-rebar-reinforced concrete and fiber-reinforced polymers. Due to its superior sound absorbing and heat resistance properties, basalt fiber is very suitable for replacing the more expensive E-glass fiber in automobile muffler and the like application. With greater friction resistance, basalt fiber is one of the most potential materials for replacing hazardous asbestos in anti-velocity and friction impacts, such as vehicle breaking plate, fluid pipe casting and the same sort. This fiber performs exceptionally well in salty and alkaline environment, making it be a best candidate for reinforcing concrete structures in such environment. Nevertheless, this fiber material could be produced lower price than other fibers at the same or lower quality.

Thailand as an industrializing country in Southeast Asia needs fiber for various industrial applications ranging from fiber reinforced roof tiles, walls and ceiling boards, fiber-reinforce concrete and polymer, sound absorbing and insulation fiber fabric as well as friction resistance applications. Since asbestos is widely used and their hazardous awareness increased, invention of low cost substitute material like basalt fiber is very crucial for sustainability. The study on potential of producing basalt fiber from Lopburi basalt has come to conclusion as below:

A. Geologically Lopburi basalts from the three tenements occurred to be moderately variable in terms of petrography and physical properties. From geological investigation Khok Chareon tenement found to be the most suitable location among the three, due to the less geological variation. This tenement was observed to have fewer lithological variation, less weathering as well as less alteration. Fresh or unaltered basalts are mostly found in this tenement, which increase ability of having larger resources (see Table 5-1). In production perspective, less varied reserve is very preferable and convenient in grade control. Although occurred to be highly altered and varied, the other two tenements also consist of unaltered and fresh basalt resources. With higher lithological variation and alteration, it would be inconvenient for commercial production due to the difficulties in grade controlling. However, small scale production, which required less resources, could be feasible if other economic factors are included.

Table 5-1: Summarized physical characteristics of basalts in Lopburi

Tenements	Alteration and Weathering	Lithology Variation
Khok Chareon	Slightly altered & Strong mechanically weathered	Slightly varied
Chai Badan	Highly altered and strong chemically weathered	Highly varied
Khok Samrong	Moderately altered & Slightly weathered	Slightly varied

B. Geochemically, Lopburi basalts contain high concentration of alkalis which had been originated from calc-alkaline to High-K calc-alkaline magma series. With high alkalinity, basalts in Lopburi could produce less acid stability fiber, but better alkalinity resistance. The average of Lopburi basalts has relatively high acidity and viscosity modulus, which have potential to produce continuous fiber with good strength, intermediate thermal insulation and less ability for crystallization since it contains relatively low iron and high alumina. Having high viscosity and acidity requires high temperature for melting and spinning process, resulting in high manufacturing cost. However, after investigated, not all basalt of Lopburi are followed the average. Some of them has considerable low viscosity and acidity modulus, which have potential to produce cheaper fiber with lower strength fiber, but acceptable insulation and sound absorbing property. Nonetheless, some samples exhibit to be very high in acidity modulus, indicated by greater silicon and aluminum oxides, which is good for virtuousness and intermediate temperature application (see Table 5-2). In conclusion basalt resources in Lopburi have potential to make fiber with three different categories mentioned above.

Table 5-2: Lopburi basalt ore classification

Criteria	Ore for staple fiber	Ore for CBF	Ore for intermediate temp. application
SiO_2 wt.%	45% – 50%	50% – 55%	55% – 65%
M_a	3.0 – 4.5	4.5 – 7.0	> 7.0
M_v	1.5 – 2.5	2.5 – 4.0	> 4.0

C. Melting curve analysis shows that group of basalt from Lopburi selected have Log. viscosity in between 1.2 and 2.5 Pa*s within temperature range of 1450 – 1500 ^{o}C, which is a suitable melting range for commercial application.

In summary, basalt resources in Lopburi province of Thailand are composed of moderately varied lithology and alteration. However, present of unaltered and fresh basalt are observed across the area with reasonable resources. Based on geochemistry and melting curve analysis, basalt resources of Lopburi have potential to produce three categories of basalt fibers, brittle fiber, high quality continuous basalt fiber and high temperature application fiber. Basalt ore for brittle fiber and continuous basalt fiber could be melt at temperature range of 1450-1500 ^{o}C with viscosity of Log. viscosity of 1.2 – 2.5 Pa*s.

5.2. Recommendations

For better resource conservation and reducing cost for material modification such as dolomite modification, blending basalt ores from the three categories is recommended to achieve desirable ore qualities.

Khok Chareon was suggested to be potential area, based on lithology and physical properties only; geochemistry of basalt rock should be analyzed and checked with the results of samples studied in this research. Land use and economic factors should also be considered in selecting suitable area for basalt fiber manufacturing.

Further research should focus on melting test of basalt samples with chemical composition selected in this research to check actual viscosity, melting points and recrystallization behaviors of these basalts.

Basalt samples within chemical composition range selected in this research could be used to draw fiber in later test to verify their strength, heat resistance, stability in alkalinity and acidity, and so on.

REFERENCES

1. Kumbhar, V.P., *An Overview: Basalt Rock Fibers-New Construction Material.*
2. Sim, J. and Park, C., *Characteristics of basalt fiber as a strengthening material for concrete structures.* Composites Part B: Engineering, 2005. **36**(6): p. 504-512.
3. Novitskii, A., *High-temperature heat-insulating materials based on fibers from basalt-type rock materials.* Refractories and Industrial Ceramics, 2004. **45**(2): p. 144-146.
4. Ivanitskii, S. and Gorbachev, G., *Continuous basalt fibers: production aspects and simulation of forming processes. I. State of the art in continuous basalt fiber technologies.* Powder Metallurgy and Metal Ceramics, 2011. **50**(3-4): p. 125-129.
5. Zumberge, J.H., Rutford, R.H., and Carter, J.L., *Laboratory manual for physical geology*. 1991: Wm. C. Brown Publishers.
6. Irvine, T. and Baragar, W., *A guide to the chemical classification of the common volcanic rocks.* Canadian journal of earth sciences, 1971. **8**(5): p. 523-548.
7. Kuno, H., *Differentiation of basalt magmas.* Basalts, 1968. **2**(3): p. 623-688.
8. Pisciotta, A., Perevozchikov, B., Osovetsky, B., Menshikova, E., and Kazymov, K., *Quality Assessment of Melanocratic Basalt for Mineral Fiber Product, Southern Urals, Russia.* Natural Resources Research, 2015. **24**(3): p. 329-337.
9. Morozov, N., Bakunov, V., Morozov, E., Aslanova, L., Granovskii, P., Prokshin, V., and Zemlyanitsyn, A., *Materials based on basalts from the European North of Russia.* Glass and Ceramics, 2001. **58**(3-4): p. 100-104.
10. Kamiya, S., Tanaka, I., Imamura, K., Sasaki, H., and Nakagawa, N., *Comprising a mixture of two basalt rock containing different amounts of raw material whter the first contains more silicon dioxide thanthe second; crystal growth and bind inhibition; superior heat resistance and acoustics for automobile mufflers; cost efficiency*. 2010, Google Patents.

11. Van de Velde, K., Kiekens, P., and Van Langenhove, L. *Basalt fibres as reinforcement for composites*. in *Proceedings of 10th international conference on composites/nano engineering, University of New Orleans, New Orleans, LA, USA*. 2003.

12. Wei, B., Cao, H., and Song, S., *Environmental resistance and mechanical performance of basalt and glass fibers.* Materials Science and Engineering: A, 2010. **527**(18): p. 4708-4715.

13. Jong-Sung, Y. and Khagram, S., *A comparative study of inequality and corruption.* American Sociological Review, 2005. **70**(1): p. 136-157.

14. Singha, K., *A short review on basalt fiber.* International Journal of Textile Science, 2012. **1**(4): p. 19-28.

15. Fiore, V., Di Bella, G., and Valenza, A., *Glass–basalt/epoxy hybrid composites for marine applications.* Materials & Design, 2011. **32**(4): p. 2091-2099.

16. Li, W. and Xu, J., *Impact characterization of basalt fiber reinforced geopolymeric concrete using a 100-mm-diameter split Hopkinson pressure bar.* Materials Science and Engineering: A, 2009. **513**: p. 145-153.

17. Fiore, V., Scalici, T., Di Bella, G., and Valenza, A., *A review on basalt fibre and its composites.* Composites Part B: Engineering, 2015. **74**: p. 74-94.

18. Rabinovich, F., Zueva, V., and Makeeva, L., *Stability of basalt fibers in a medium of hydrating cement.* Glass and Ceramics, 2001. **58**(11-12): p. 431-434.

19. Öztürk, B., Arslan, F., and Öztürk, S., *Hot wear properties of ceramic and basalt fiber reinforced hybrid friction materials.* Tribology International, 2007. **40**(1): p. 37-48.

20. Wang, X., Hu, B., Feng, Y., Liang, F., Mo, J., Xiong, J., and Qiu, Y., *Low velocity impact properties of 3D woven basalt/aramid hybrid composites.* Composites Science and Technology, 2008. **68**(2): p. 444-450.

21. Landucci, G., Rossi, F., Nicolella, C., and Zanelli, S., *Design and testing of innovative materials for passive fire protection.* Fire Safety Journal, 2009. **44**(8): p. 1103-1109.

22. Novitskii, A. and Sudakov, V., *An unwoven basalt-fiber material for the encasing of fibrous insulation: an alternative to glass cloth.* Refractories and Industrial Ceramics, 2004. **45**(4): p. 239-241.

23. Metcalfe, I., *Late Palaeozoic and Mesozoic palaeogeography of southeast Asia.* Palaeogeography, Palaeoclimatology, Palaeoecology, 1991. **87**(1): p. 211-221.

24. Intasopa, S.B., *Petrology and geochronology of the volcanic rocks of the central Thailand volcanic belt*. 1993: University of New Brunswick (Canada).

25. Bunopas, S., *Paleogeographic history of western Thailand and adjacent parts of South-east Asia: a plate tectonics interpretation*. 1982: Geological Survey Division, Department of Mineral Resources.

26. Fang, W., Van der Voo, R., and Liang, Q., *Devonian paleomagnetism of Yunnan Province across the Shan Thai-South China Suture.* Tectonics, 1989. **8**(5): p. 939-952.

27. Gatinsky, Y., *Geological map of Indo-China Peninsula and adjacent territories 1: 2,500,000.* All-union Scientific Research Institute of Geology of Foreign Countries, Moscow, 1983.

28. Tapponnier, P., Meyer, B., Avouac, J.P., Peltzer, G., Gaudemer, Y., Shunmin, G., Hongfa, X., Kelun, Y., Zhitai, C., and Shuahua, C., *Active thrusting and folding in the Qilian Shan, and decoupling between upper crust and mantle in northeastern Tibet.* Earth and Planetary Science Letters, 1990. **97**(3): p. 382-403.

29. Hooper, W.F., *Peripheral geology of the Southern Chao Phya Plain Prog.* Report No. 1 of Thailand Gulf Oil Co., The Dept of Mineral Resources, open file, 1969.

30. Polachan, S., Pradidtan, S., Tongtaow, C., Janmaha, S., Intarawijitr, K., and Sangsuwan, C., *Development of Cenozoic basins in Thailand.* Marine and Petroleum Geology, 1991. **8**(1): p. 84-97.

31. Barr, S. and MacDonald, A., *Geochemistry and geochronology of late Cenozoic basalts of Southeast Asia.* Geological Society of America Bulletin, 1981. **92**(8 Part II): p. 1069-1142.

32. Harker, A., *The natural history of igneous rocks*. 1909: Macmillam.

33. Le Bas, M.J., Le Maitre, R., Streckeisen, A., and Zanettin, B., *A chemical classification of volcanic rocks based on the total alkali-silica diagram.* Journal of petrology, 1986. **27**(3): p. 745-750.

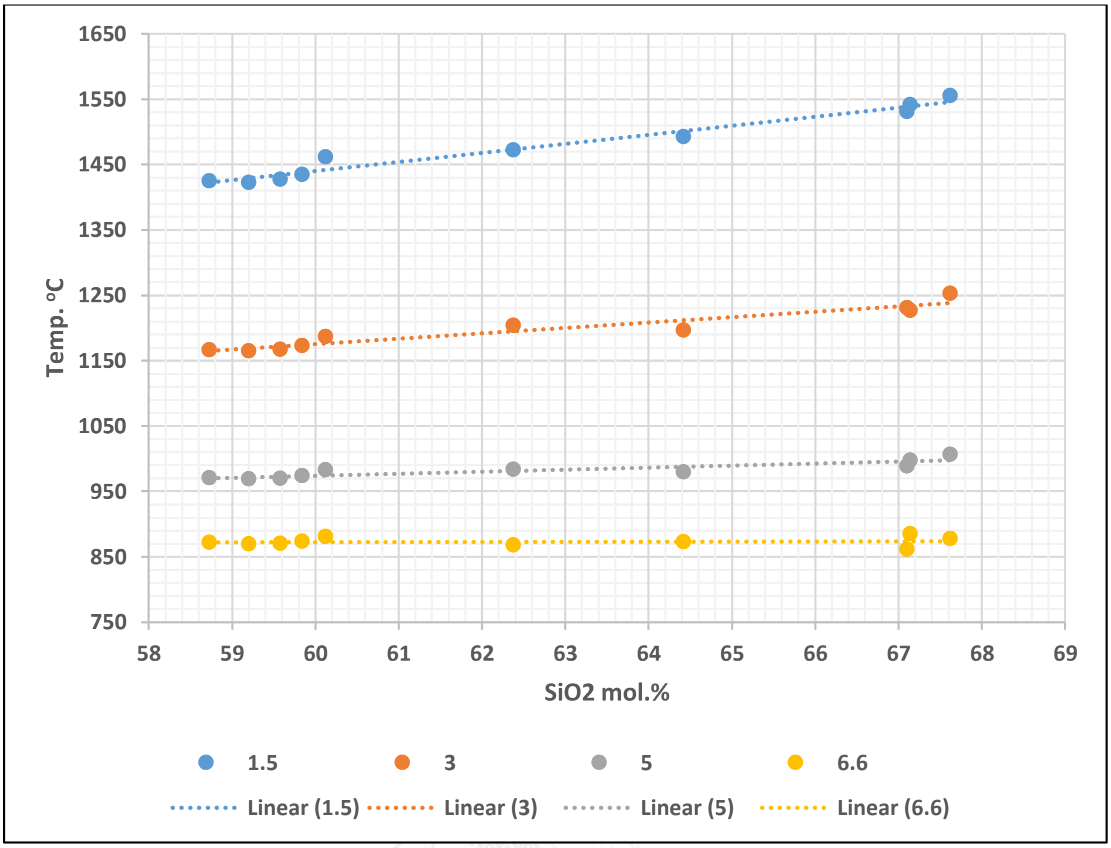
34. Cox, K.G., *The interpretation of igneous rocks*. 1979: Springer Science & Business Media.

35. Peccerillo, A. and Taylor, S.R., *Geochemistry of Eocene calc-alkaline volcanic rocks from the Kastamonu area, northern Turkey.* Contributions to mineralogy and petrology, 1976. **58**(1): p. 63-81.

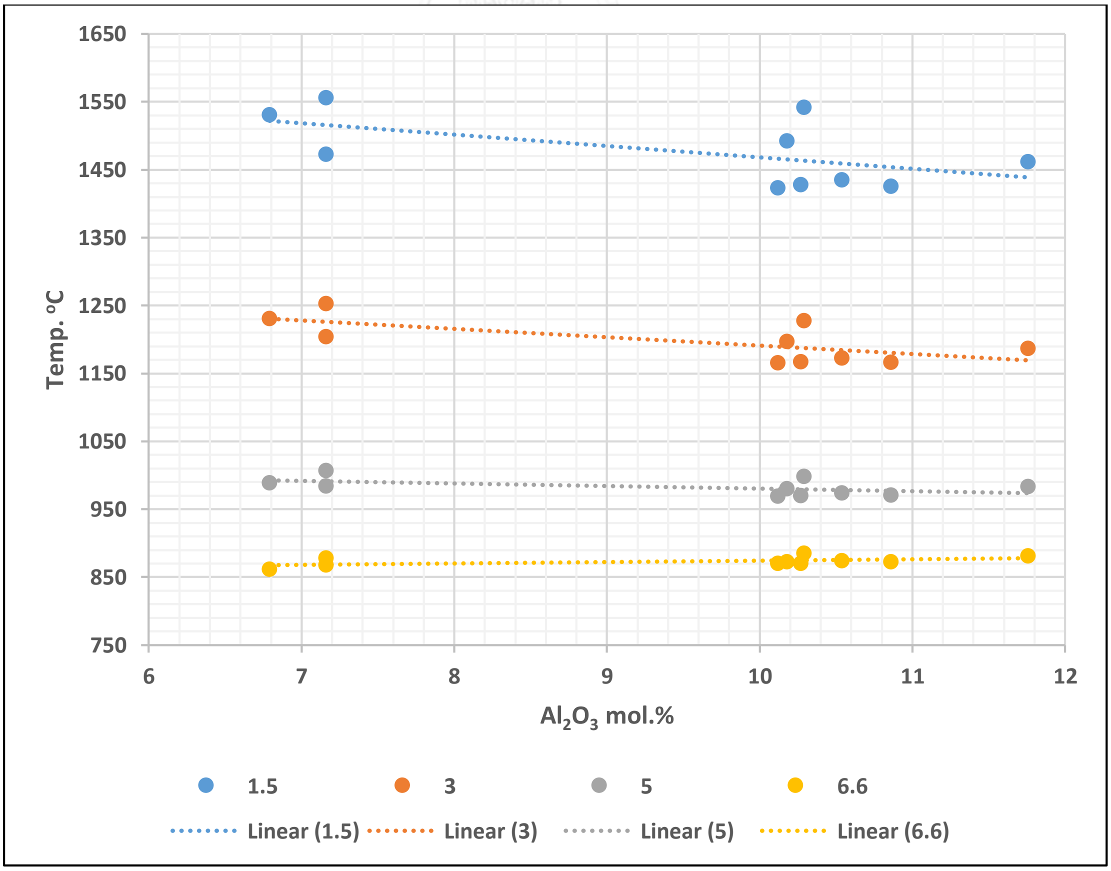
36. Apirat, T., Thanakorn, W., and Supatra, J., *The study of using glass fiber from basalt as raw materials in industry.* Feb. 2016, Chula Unisearch, Chulalongkorn University.

APPENDIX A

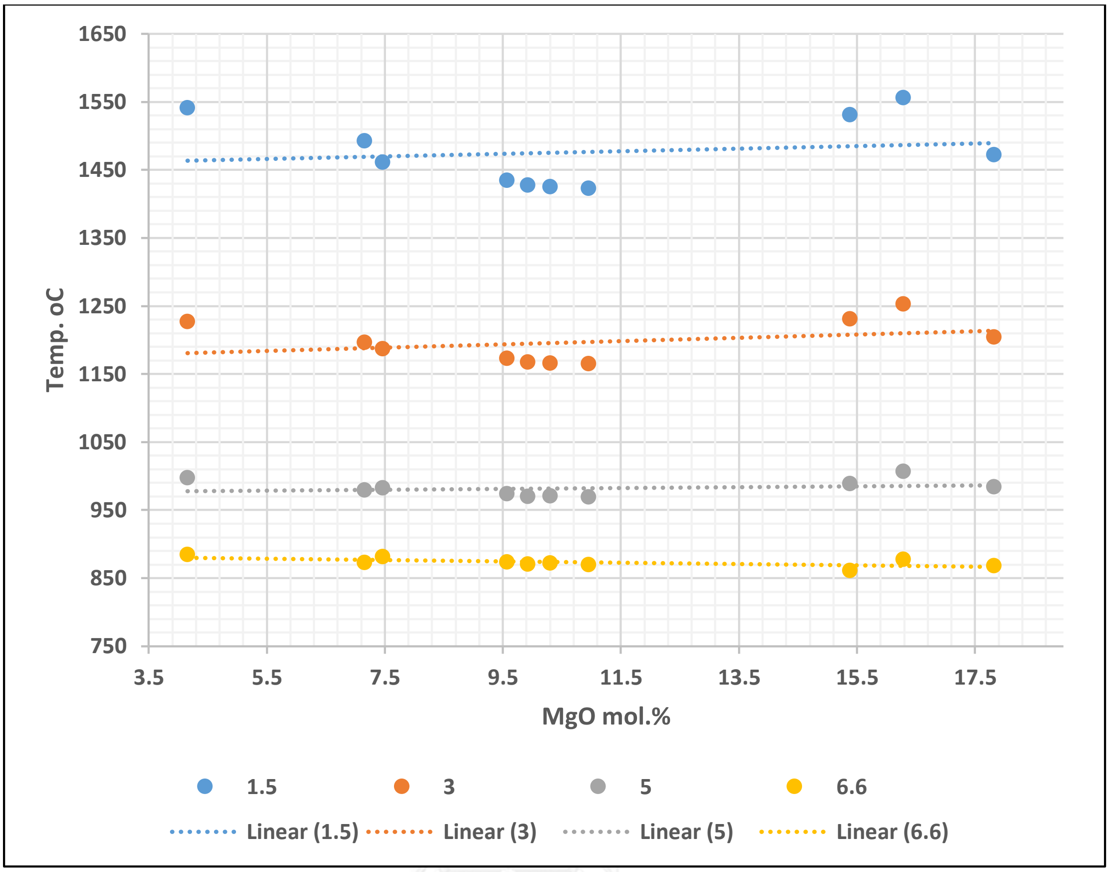
Relationship between major oxides with melting temperature at certain Log. viscosity (1.50, 3, 5 and 6.6 Pa*s)

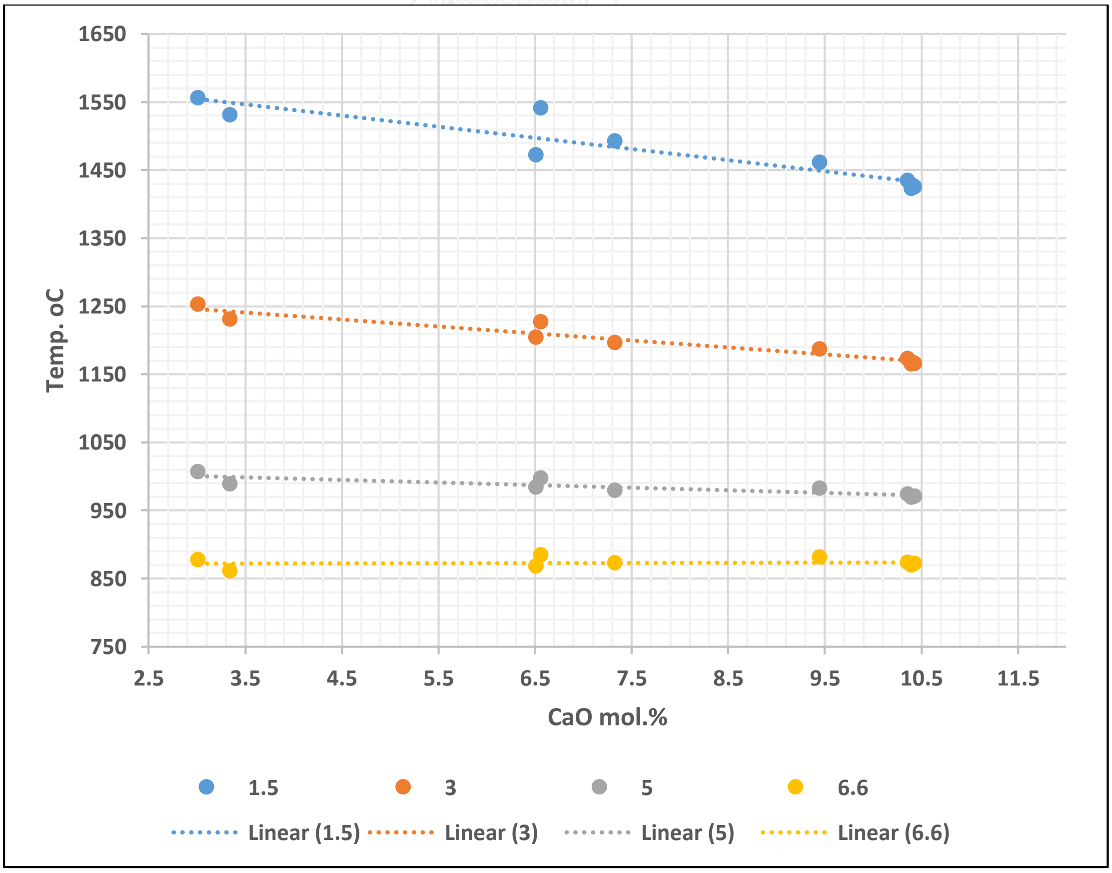


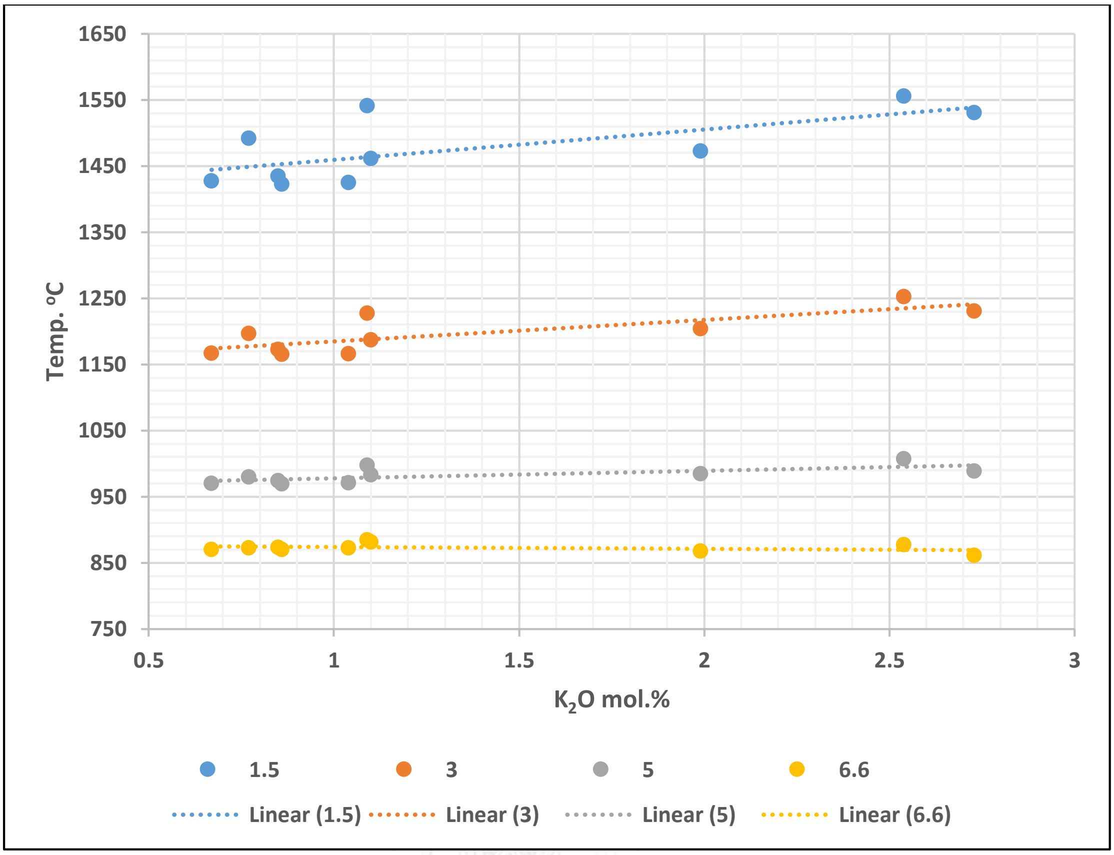
Temp. °C
1650
1550
1450
1350
1250
1150
1050
950
850
750
58
59
60
61
62
63
64
65
66
67
68
69
SiO2 mol.%
1.5
3
5
6.6
Linear (1.5)
Linear (3)
Linear (5)
Linear (6.6)

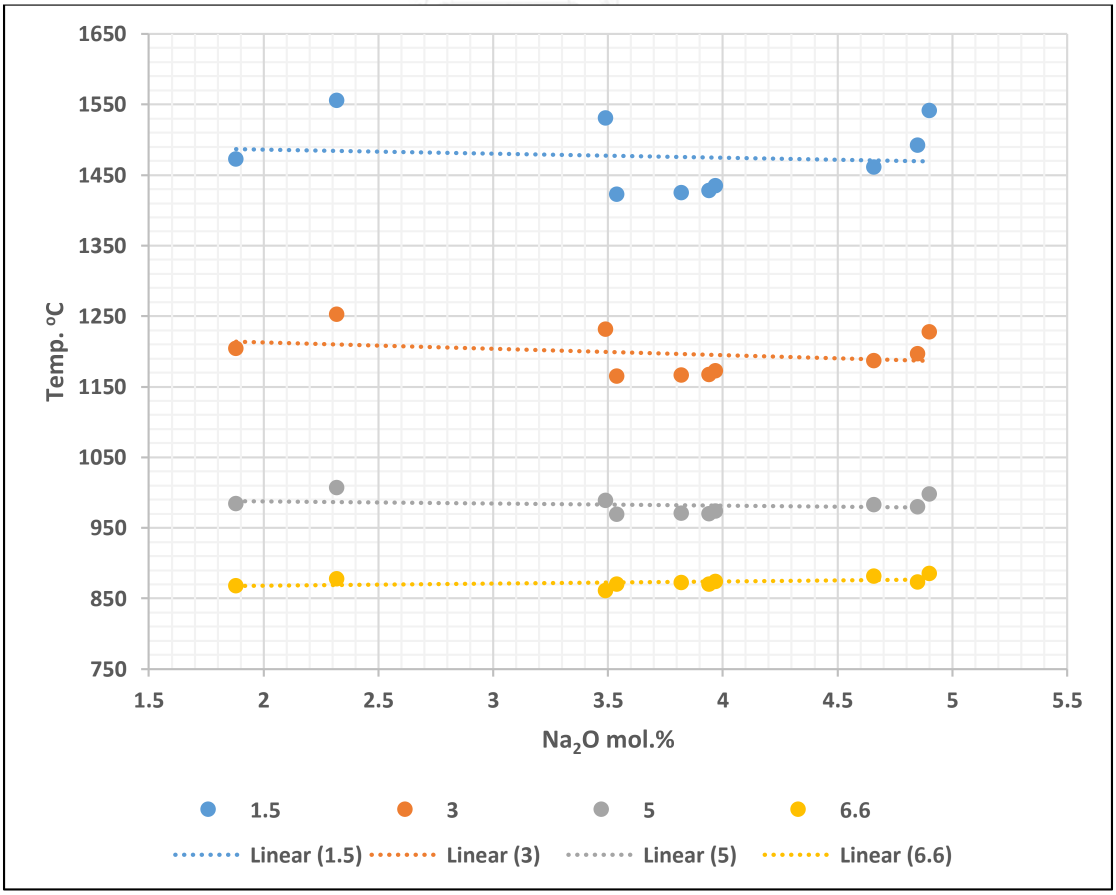


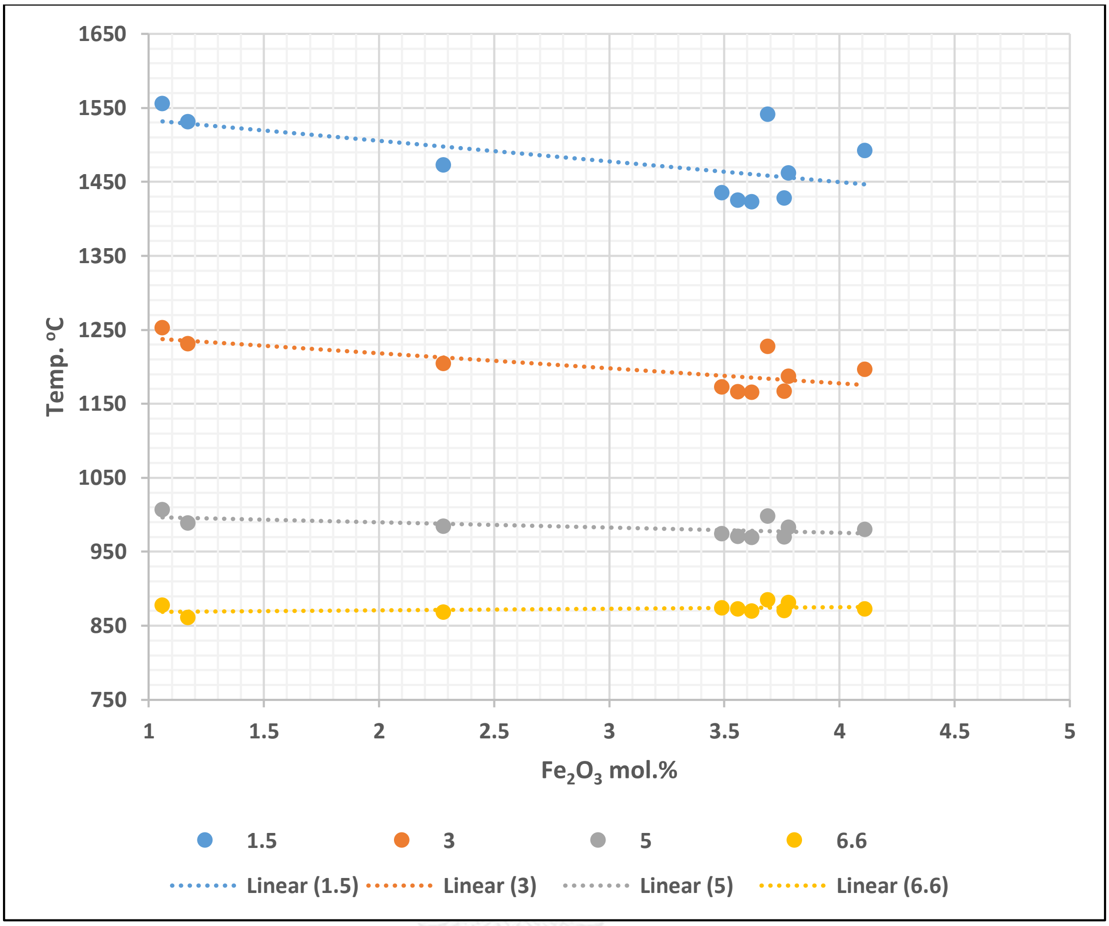
Temp. °C
1650
1550
1450
1350
1250
1150
1050
950
850
750
6
7
8
9
10
11
12
Al_2O_3 mol.%
1.5
3
5
6.6
Linear (1.5)
Linear (3)
Linear (5)
Linear (6.6)


1650
1550
1450
1350
1250
1150
1050
950
850
750
Temp. oC
3.5
5.5
7.5
9.5
11.5
13.5
15.5
17.5
MgO mol.%
1.5
3
5
6.6
Linear (1.5)
Linear (3)
Linear (5)
Linear (6.6)


1650
1550
1450
1350
1250
1150
1050
950
850
750
Temp. oC
2.5
3.5
4.5
5.5
6.5
7.5
8.5
9.5
10.5
11.5
CaO mol.%
1.5
3
5
6.6
Linear (1.5)
Linear (3)
Linear (5)
Linear (6.6)


1650
1550
1450
1350
1250
1150
1050
950
850
750
Temp. °C
0.5
1
1.5
2
2.5
3
K2O mol.%
1.5
3
5
6.6
Linear (1.5)
Linear (3)
Linear (5)
Linear (6.6)


1650
1550
1450
1350
1250
1150
1050
950
850
750
Temp. °C
1.5
2
2.5
3
3.5
4
4.5
5
5.5
Na2O mol.%
1.5
3
5
6.6
Linear (1.5)
Linear (3)
Linear (5)
Linear (6.6)


1650
1550
1450
1350
1250
1150
1050
950
850
750
Temp. °C
1
1.5
2
2.5
3
3.5
4
4.5
5
Fe2O3 mol.%
1.5
3
5
6.6
Linear (1.5)
Linear (3)
Linear (5)
Linear (6.6)

VITA

Seangleng Hoeun was born in Kampong Cham province, Cambodia on July 16, 1991. The author obtained the B.Eng in Georesources and Geotechnical Engineering from Institute of Technology of Cambodia, Phnom Penh in 2104. In the same year he attended Chulalongkorn University as full-time Master's degree student in Georesources Engineering, under ASEAN Scholarship Program of Graduate School of Chulalongkorn University. He is proceeding to be a oral presenter in international conference, "ASEAN++ 2016: Towards Geo-resources Education in ASEAN Economic Community".