PERFORMANCE OF HEMP FIBER REINFORCED CONCRETE AND NATURAL RUBBER LATEX-MODIFIED CONCRETE USING RECYCLED CONCRETE AGGREGATE AS A SUSTAINABLE RIGID PAVEMENT

BUNDAM RO

A Thesis Submitted in Partial Fulfillment of the Requirements for the Degree of Master of Engineering in Civil, Transportation and Geo-Resources Engineering

Suranaree University of Technology

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พฤติกรรมของคอนกรีตที่ใช้มวลรวมคอนกรีตรีไซเคิลเสริมด้วยเส้นใยกัญชงและน้ำยางธรรมชาติเพื่อเป็นผิวทางคงรูปอย่างยั่งยืน

นายบุญดัม โร

วิทยานิพนธ์นี้เป็นส่วนหนึ่งของการศึกษาตามหลักสูตรปริญญาวิศวกรรมศาสตรมหาบัณฑิต
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มหาวิทยาลัยเทคโนโลยีสุรนารี
ปีการศึกษา 2566

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Suranaree University of Technology has approved this thesis submitted in partial fulfillment of the requirements for a Master's Degree.

Thesis Examining Committee

(Asst. Prof. Dr. Theerawat Sinsiri)
Chairperson

(Asst. Prof. Dr. Menglim Hoy)
Member (Thesis Advisor)

(Assoc. Prof. Dr. Cherdsak Suksiripattanapong)
Member

(Assoc. Prof. Dr. Yupaporn Ruksakulpiwat)
Acting Vice Rector for Academic Affairs
and Quality Assurance

(Assoc. Prof. Dr. Pornsiri Jongkol)
Dean of Institute of Engineering

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คำสำคัญ : เส้นใยกัญชง คอนกรีตรีไซเคิล ผิวทางคอนกรีต น้ำยางธรรมชาติ ความยั่งยืน

การศึกษานี้สำรวจการใช้วัสดุที่ยั่งยืนเพื่อเพิ่มประสิทธิภาพของผิวถนนคอนกรีตโดยมุ่งเน้นไปที่ประเด็นสำคัญสองปัจจัยสำคัญ ในส่วนแรกจะตรวจสอบผลกระทบของการเพิ่มเส้นใยกัญชงในคอนกรีตเสริมใยกัญชง (HFRC) เพื่อลดความล้าแตกร้าวและยืดอายุการใช้งานของผิวทางคอนกรีต เส้นใยกัญชงถูกรวมใช้กับคอนกรีตที่มีทั้งมวลรวมหยาบธรรมชาติ (NCA) และมวลรวมคอนกรีตรีไซเคิล (RCA) โดยใช้อัตราส่วนน้ำต่อซีเมนต์ 0.5 ปริมาณเส้นใยกัญชงที่สูงขึ้นจะช่วยเพิ่มความแข็งแรงในการรับแรงดัดงอ โดยมีระดับการเสริมแรงที่เหมาะสมที่สุดที่ 0.5% สำหรับทั้ง NCA และ RCA ในการทดสอบความล้า การควบคุมและตัวอย่าง HFRC 0.5% เป็นไปตามข้อกำหนด ซึ่งบ่งชี้ถึงศักยภาพในของผิวถนนคอนกรีตที่บางและทนทาน ส่งผลดีต่อต้นทุนก่อสร้างและความยั่งยืน การศึกษายังสำรวจการทดแทนมวลรวมของเสีย รวมถึงพลาสติก PET และเศษยางในคอนกรีต มีการประเมินกำลังรับแรงอัดและแรงดัดงอ โมดูลัสความยืดหยุ่น และความเหนียว ซึ่งเผยให้เห็นว่าอัตราส่วนการแทนที่รวมที่สูงขึ้นจะช่วยลดกำลังรับแรงอัดและแรงดัดงอ การวิเคราะห์ด้วยกล้องจุลทรรศน์อิเล็กตรอนแบบส่องกราด (SEM) เน้นย้ำถึงการเปลี่ยนแปลงโครงสร้างจุลภาคที่เกิดจาก PET และเศษยาง ส่งผลให้ซีเมนต์เพสต์และมวลรวมสัมผัสกันไม่ดี อย่างไรก็ตาม การเติมน้ำยางธรรมชาติ (NRL) ช่วยเพิ่มความแข็งแรงของพันธะ ทำให้เกิดโครงข่ายฟิล์มที่ทำหน้าที่เป็นกลไกในการประสารกันของมวลรวม การเปลี่ยนไปใช้ PETทดแทนวัสดุธรรมชาติ และเศษยาง 10% ในการผสมคอนกรีตด้วย NRL เป็นไปตามข้อกำหนดขั้นต่ำสำหรับการก่อสร้างถนนที่ยั่งยืนและช่วยลดวัสดุเหลือใช้และลดผลกระทบต่อสิ่งแวดล้อม

สาขาวิชา วิศวกรรมโยธา

ปีการศึกษา 2566

ลายมือชื่อนักศึกษา ....

ลายมือชื่ออาจารย์ที่ปรึกษา ....

BUNDAM RO: PERFORMANCE OF HEMP FIBER REINFORCED CONCRETE AND NATURAL RUBBER LATEX-MODIFIED CONCRETE USING RECYCLED CONCRETE AGGREGATE AS A SUSTAINABLE RIGID PAVEMENT
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This study investigates the incorporation of sustainable materials in concrete pavement to enhance its performance. Initially, the research examines the role of hemp fiber in hemp fiber-reinforced concrete (HFRC) to improve fatigue performance and prolong pavement service life. Hemp fiber is mixed into concrete using both natural coarse aggregate (NCA) and recycled concrete aggregate (RCA). The results indicate that the hemp fiber content is optimized at 0.5% for both NCA and RCA, identified as the most effective concentration for enhancing flexural strength and fatigue performance compared to the control samples. Subsequently, the study explores the use of natural rubber latex (NRL) in modifying concrete for rigid pavement with the substitution of waste aggregates like PET plastic and crumb rubber. The research assesses various properties such as compressive and flexural strengths, modulus of elasticity, and toughness. Findings indicate that higher ratios of these waste aggregates tend to lower the compressive and flexural strengths. Scanning electron microscopy (SEM) analysis indicated that the poor bond strength between cement pastes and these aggregates is a significant factor in their reduced performance. Integrating NRL enhances the bond strength, creating a film network that acts as a bridging mechanism. A 10% replacement of PET and crumb rubber, blended with NRL-modified concrete, meets the minimum standards for sustainable road construction. This approach offers the dual benefit of reducing waste materials and lessening environmental impact.

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Student's Signature..................
Advisor's Signature..................

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SYMBOLS AND ABBREVIATIONS

AASHTO	=	American association of state highway and transportation officials
Al_2O3	=	Aluminum oxide
ASTM	=	American society for testing and materials
b	=	Width of beam specimen
CaO	=	Calcium silicate hydrate
CSH	=	Calcium silicate hydrate
d	=	Depth of beam specimen
DoH-S	=	Department of highway standard
DOH	=	Department of highway, Thailand
EDX	=	Energy dispersive X-ray
FA	=	Fine aggregate
Fe_2O_3	=	Iron oxide
f_f	=	Flexural strength
FHWA	=	Federal highway administration
FRC	=	Fiber reinforced concrete
GPa	=	Gigapascal
HRWR	=	High-range water reducer
$Kg.m^{-3}$	=	Kilogram per cubic meter
L	=	Length from support to support of beam specimen
LOI	=	Loss on ignition
MEPDG	=	Mechanistic-empirical pavement design guide
MgO	=	Magnesium oxide
MJ/m^3	=	Megajoule per cubic meter
MOR	=	Modulus of rupture
MPa	=	Megapascal
MRWR	=	Medium-range water reducer

SYMBOLS AND ABBREVIATIONS (Continued)

NaOH	=	Sodium hydroxide
b	=	Width of beam specimen
CaO	=	Calcium silicate hydrate
CSH	=	Calcium silicate hydrate
NCA	=	Natural coarse aggregate
NCA-H-FRC	=	Hemp fiber reinforced concrete using natural coarse aggregate
NCHRP	=	National cooperative highway research program
NRL	=	Natural Rubber Latex
N_f	=	Number of cycles at failure
OPC	=	ordinary Portland cement
P	=	Apply vertical load
PCA	=	Portland cement association
RCA	=	Recycled concrete aggregate
RCA-H-FRC	=	Hemp fiber reinforced concrete using recycled concrete aggregate
SEM	=	Scanning electron microscope
SiO_2	=	Silicon dioxide
SO_3	=	Sulfur trioxide
SR	=	Stress ratio
vol.	=	Volume
W	=	Water
w/c	=	Water to cement ratio
wt.	=	Weight
ε	=	Strain
σ	=	Stress
$\overline{x}$	=	Mean strength value

CHAPTER I
INTRODUCTION

1.1 Background

Thailand is a country under developing which requires a remarkable progress in implementation of multilayer large public infrastructure projects. Transportation is one of the main roots to link the roadways to the city. Moreover, land transport is the easiest way for people in Thailand to travel because of the affordable price of traveling and owning vehicles. While the demand for using vehicles still increases annually, the new road constructions also grow yearly. In contrast, investment on pavement and maintenance project are the most expensive infrastructures, which essentially needs tremendous of quarry stones to construct and can be estimated the amount of aggregate uses in pavement construction approximately between 60 to 80 percentages. A huge number of natural resources has been extracted to manipulate in construction industries rapidly, which must be operated with large machines that requisite significant fuels and identically, continue causing many environmental impacts in unpleasant ways result in climate change from greenhouse gas emission. Therefore, Thailand's government policy has encouraged to find many alternatives to reduce 30 percentage of carbon emissions in 2030. For this purpose, a sustainable infrastructure will be introduced as a key strategics initiative and at the forefront of pavement industries and researcher to be comply with the circular economy.

According to The Nation Thailand in 2021, the budget of 175.85 billion Thai baht counted as 5.7 percentages of the total budget in 2022 has been managed to use in transportation ministry, which illustrates that massive amount of budget has been promoted for road construction. Pavement structures based on constituent materials are divided into two different types which are flexible pavement (asphalt concrete pavement) and rigid pavement (concrete pavement). Focusing on concrete road, the components to build the concrete are fine aggregate, natural coarse aggregate (NCA), cement and the water, which NCA contains the most ratio compared to overall materials that has the role to strengthen the concrete and correspondingly to fine aggregate and cement which has the role to bond and fill the gaps between granular materials. Recycled concrete aggregate (RCA) is a great substitution for NCA, which is the waste from demolished buildings or old concrete roads and tested samples from concrete ready-mix plants to reuse. Concrete waste is not biodegradable material that requires a massive land to store, and researchers have been studied on RCA to be used in construction application because of its physical stiffness as a sustainable and environmentally eco-friendly pavement. However, the service life of the pavement is dependent on the volume of usage which separates into heavy traffic volumes (greater than a million traffic loads) and lower traffic volumes (less than ten thousand loads). Excluding compressive strength, there are few more factors to shorten its service life and lose of interest such as creating high greenhouse gas emission, low tensile, low flexural strength, and fatigue life (Chan et al., 2019; Krishna et al., 2014). Thus, to prevent its weakness, thicker thickness is required to resist immature failure due to axle loading of the vehicles. For this purpose, pavement engineers and researchers have been developed technologies and methods for improving flexural strength, for instant, synthetic fibers (steel and glass fibers, polyolefin fibers, and polyvinyl alcohol fibers) have been proven as effective and increasingly used as fiber-reinforced concrete (FRC) pavement. Conversely, producing a large number of synthetic fibers requires high energy consumption and causes heavy pollution to the environment. Hence, the use of natural fibers will be a replacement with the enlargement of interest in both academic research and industrials applications.

At current years, there have been significant developments in the field of sustainable construction materials, such as innovation involving the incorporation of PET plastics and waste tires in concrete pavement (Saikia and De Brito, 2012; Youssf et al., 2016). Waste tried can be made into crumb rubber particles and used in the concrete mix as a sand replacement (Park et al., 2016). Utilizing crumb rubber lessens the need for sand mining, protecting natural resources and lessening its negative effects on the environment. PET plastic bottles can also be broken down into small particles and used as a coarse aggregate replacement in the concrete mix (Islam et al., 2016). However, the utilization of PET and waste tires in concrete mix resulted in the reduction of flexural strength (modulus of rupture) of concrete, which is an important property for concrete pavement. Therefore, additional additives might enhance the properties of concrete in rigid pavement applications. In terms of sustainable road construction, Yaowarat et al. proposed an innovative idea of value-added natural rubber latex (NRL) as a green additive and studied the influence of various ratios of rubber-to-cement (r/c) on the development of strength of nor-mal concrete (Yaowarat et al., 2021). It indicated that the ideal rubber ratio in concrete could improve concrete’s modulus of rupture, resulting in the long service life of the rigid pavement.

Nevertheless, in recent years, hemp has the potential as a cash crop globally and Thailand government has been promoted farmers to cultivate with perceived utilization in downstream industries for various purposes. Consequently, hemp will not be easily adopted by farmers until value-added processing is established. In current situation, hemp has been sold in the form of straw and seeds which will not produce significant revenue to attract farmers, whereas promoting financially hemp processing business is one of the best methods to claim the interest in hemp cultivation. To strengthen the social economic if agricultural sector in Thailand, the possibility of studying of using hemp fibers in wide-reaching as the construction industrial materials might vitalize the publics and private sectors to invest in the cultivation of an industrial crop. The hemp fiber reinforced material application has been studied in the construction fields such as lime-hemp plaster, hemp concrete, hempcrete, polymeric hemp-based composite and lightweight hemp concrete, which are mostly non-structural loading applications. In contrast, to take advantages of hemp fiber-reinforced concrete in road construction has been very limited, even though pavement is the largest construction industry in Thailand. Due to the lack of field and laboratory experimental investigation which resulted in unable to develop a new mix design method to reach the target of flexural strength and fatigue performance and a mechanistic design method for hemp fiber-reinforced concrete as a rigid pavement. To obtain the objective, compression strength, flexural strength and flexural fatigue tests will be examined with a complete set of geotechnical and pavement laboratories at Center of Excellence in Innovation for Sustainable Infrastructure Development, Suranaree University of Technology.

Subsequently, according to socio-economic and environmental development purpose, this research study aims to scrutinize the compressive strength, flexural strength, and flexural fatigue responses of sustainable hemp fiber reinforced concrete pavement using RCA at difference mixing proportion of water to cement ratio, RCA, and hemp replacement ratios. The outcome will be analyzed to provide an effective mix design method and a mechanistic pavement design method for sustainable hemp fiber reinforced concrete pavement, which can provide both economic and environmental benefits.

1.2 Purpose of the Research

The focus of this research is to develop sustainable mix designs for concrete pavement by combining hemp fiber and natural rubber latex with waste polymers such as PET and crumb rubber. This study aims to explore innovative solutions for rigid pavement construction with the following specific objectives:

I. To investigate the performance, including durability and strength, of natural rubber latex-modified concrete with crumb rubber and recycled PET plastic aggregate as a rigid pavement material.

II. To assess the effectiveness of hemp fiber reinforced concrete, utilizing recycled concrete aggregate, in terms of its structural integrity and sustainability for rigid pavement applications.

III. To explore the fatigue performance of hemp fiber reinforced concrete, employing recycled concrete aggregate, under flexural cyclic loading, aiming to understand its resilience and longevity in pavement applications.

This research is poised to contribute significantly to the field of sustainable construction, potentially leading to more environmentally friendly and durable pavement solutions.

1.3 Scope of the Research

This research aims to evaluate the effect of hemp fibers and the replacement of NCA with RCA on compression strength, flexural strength, and flexural fatigue properties of concrete pavements. The scope of this work are as follows:

I. Study the effect of setting time of cement paste in various w/c ratios with the volume content of hemp fibers.

II. Study the effect of w/c ratio, hemp fiber content using RCA content, and waste polymer concrete using natural rubber latex on the compressive strength and flexural strength development under static loads of normal strength concrete pavement.

III. Investigate the bonding behavior of concrete materials by using SEM for hemp fiber reinforced-concrete and natural rubber latex-modified concrete.

IV. Study the effect of w/c ratio, hemp fiber content, and RCA content on the fatigue performance and crack mechanism under cyclic load test of normal strength concrete pavement.

V. Propose the practical mix design and design method for concrete pavement using hemp fiber and recycled concrete aggregate as a sustainable material.

1.4 Research Questions

The current research raises several questions to achieve research objective:

I. How does natural coarse aggregate (NCA) have negative effects to the environment?

II. How many tons of waste concrete are at cement plant and demolishment of concrete structure?

III. How to recycle concrete waste for use in the construction industry?

IV. Can waste polymer such as PET and crumb rubber be used in concrete?

V. Can natural rubber latex improve the mechanical strength of concrete?

VI. What is the appropriate amount of waste polymer to improve the concrete?

VII. Is there a significant strength effect on replacing NCA with RCA for concrete mix design?

VIII. Are there any changes of treated hemp fiber compared to natural hemp fiber?

IX. How does hemp FRC affect the strength in difference volume?

X. How does the hemp fiber reinforce concrete response to repeated loads?

1.5 Expected Contribution of the Research

The expected contributions of the proposed research objectives are as follow:

I. Able to identify the effective treatment of hemp fiber to use as a reinforcement in concrete with the optimum amount of volume in concrete.

II. Comparison of concrete using RCA and NCA for compression strength and flexural strength to use for the pavement.

III. Able to know the appropriate amount of waste polymer usage for NRL concrete.

IV. The improvement of concrete by using natural rubber latex.

V. Able to find a relationship between flexural strength and compression strength of sustainable concrete.

VI. Improvement of the flexural strength and flexural fatigue for hemp fiber reinforced concrete and NRL Concrete.

CHAPTER II

LITERATURE REVIEWS

2.1 Previous Studies on Recycled Concrete Aggregate (RCA)

The speedy increment of economic and social development results in an increasing tremendous number of needs in civil infrastructures. In the construction industry, there are two types of structure which are steel and concrete structure. Steel structure is not commonly used for normal structures because of its cost and difficulty of forming in shape that must be ordered from the manufacturer. In addition, steel components require hug truck for transportation which is the additional cost on it and the crane for lifting to assemble at construction site and need a professional labor to build, whereas concrete structure is globally used according to the price and the material that can be found all over the world. Similarly, concrete has advantages on casting into complexity shape, simple for transportation, compressive strength and especially cheaper than steel structure. Due to Behera et al. in 2014, 25 billion tons of concrete are manufactured worldwide. Concrete also has its own service life of approximately 50 years for reinforced concrete which means the unserviceable structures must be destroyed and disposed to the landfill site and resulted in not economically and environmentally sustainable. Moreover, extracting the natural coarse aggregate (NCA) from natural resources to utilize in concrete mixing causes the unbalance of ecological and generally pollutes the environment. Despite the convenience of concrete, there are waste management should be considered after out of life span. Therefore, waste concrete can be crushed to any size to reuse and namely as recycled concrete aggregate (RCA). The benefits of RCA are to lower in decreasing environmental pollution and require landfill. Instead of delivering NCA from explosive quarry, RCA can be found at cement plants and close to the city which can save transportation cost and the energy of crushing. According to Ponikiewski et al. in 2014, RCA has a problem with consistency which depends on the water to cement ratio and type of cement of the mixing. Correspondingly, RCA contains cement mortar attached to NCA which has high porosity and leads to higher water absorption compared to NCA.

2.2 Influence of Replacing RCA in Concrete as Coarse Aggregate

Safiuddin et al. in 2021 proposed a method to replace NCA with RCA in amount of 0, 30, 50, 70, and 100% of high workability of concrete and tested in compressive strength, split tensile strength, flexural strength, and modulus of elasticity to observe the behavior of sustainable concrete. The concrete mixing components have NCA from crushed granite stone and RCA from ready-mix plant as coarse aggregate with the maximum size of 20 mm, quartz river sand as fine aggregate, ordinary Portland cement with specific gravity of 3.12, tape water and a polycarboxylate based high-range water reducer (HRWR) of 1.06 specific gravity to ensure the workability. The gradation curve of coarse aggregate is shown in Figure 2.1 and the properties of coarse aggregate and fine aggregate in Table 2.1. The concrete was mixed in 3 differences water to cement ratios (0.50, 0.60, and 0.65) with the nixing proportion from Table 2.2 to observe the workability by using a rotary pan mixer and cast into 100 mm cubes for compression test, Ø 100 mm × 200 mm cylinder for split tensile test, and 100 mm × 100 mm × 200 mm prism for flexural strength test.

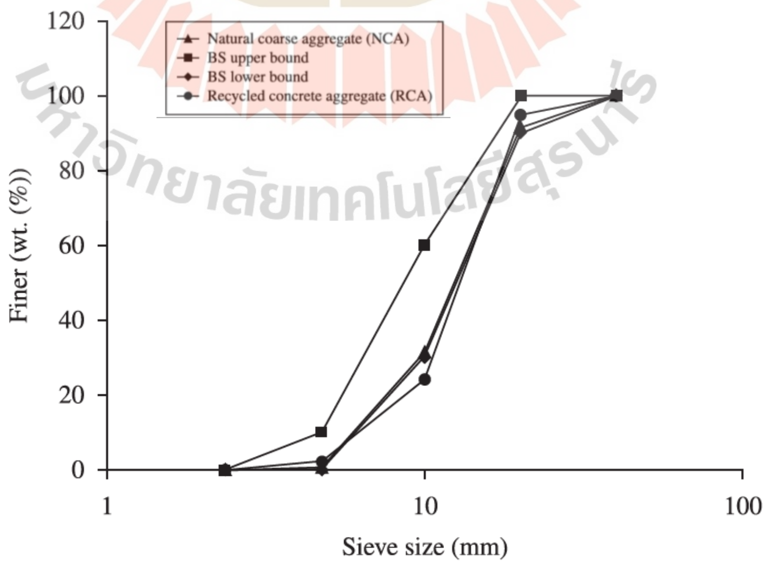


Figure 2.1 Gradation curve of natural coarse aggregate and recycled concrete aggregate (Safiuddin et al., 2011).

Table 2.1 Physical properties of fine and coarse aggregate (Safiuddin et al., 2021).

Physical Properties	RCA	NCA	FA
Maximum size aggregate (mm)	20	20	5
Fineness modulus	6.79	6.76	2.88
Bulk density (kg.m^{-3})	1250	1510	1620
Saturated surface dry specific gravity	2.53	2.62	2.69
Oven-dry based specific gravity	2.48	2.53	-
Open porosity (vol. (%))	5.03	1.55	-
Absorption (wt. (%))	2.03	0.60	1.32
Moisture content (wt. (%))	1.57	0.17	0.31
Angularity number	9.50	7.50	-
Aggregate impact value (wt. (%))	12.7	10.0	-

Table 2.2 Concrete mix proportions (Safiuddin et al., 2011).

Mix	NCA (kg.m^{-3})	RCA (%CA)	RCA (kg.m^{-3})	FA (kg.m^{-3})	OPC (kg.m^{-3})	W (kg.m^{-3})	HRWR (%C)
CRCA0	910	0	0	905	342	214	1.5
CRCA30	609	30	261	865	342	214	1.5
CRCA50	433	50	433	861	342	214	1.5
CRCA70	259	70	604	858	342	214	1.5
CRCA100	0	100	857	852	342	214	1.5

According to the test results in figure 2.2, the slump flow was reduced in a small amount by the percentage replacement respectively which can be maintained by using HRWR. Along with compressive strength from figure 2.3, at 7 and 28 days the strength was minor deducted but surprisingly for flexural strength had almost equally the strength at 100 percentage of replacement due to figure 2.4. Following with modulus of elasticity in figure 2.5, it had a significant reduction in substitution of RCA and similarly to flexural test, the splitting tensile test had a tiny decrease in 100 percentage by weight replacement in figure 2.6.

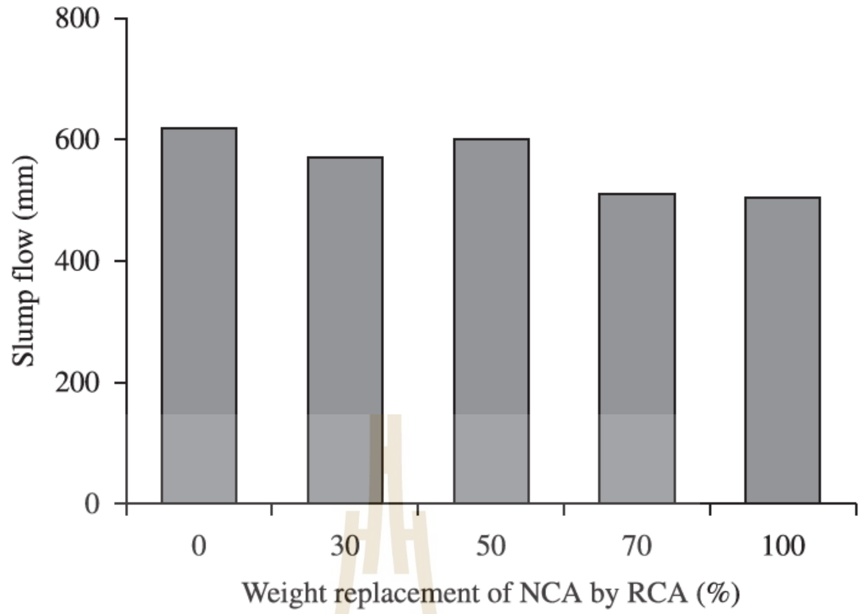


Figure 2.2 Replacement of RCA in concrete slump flow (Safiuddin et al., 2011).

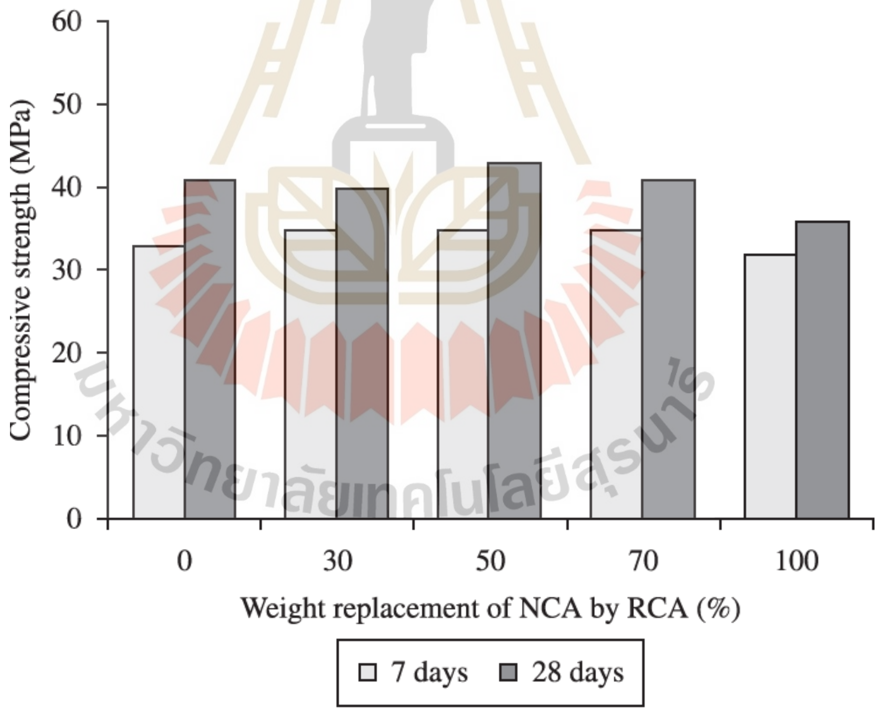


Figure 2.3 Replacement of RCA in compressive strength (Safiuddin et al., 2011).

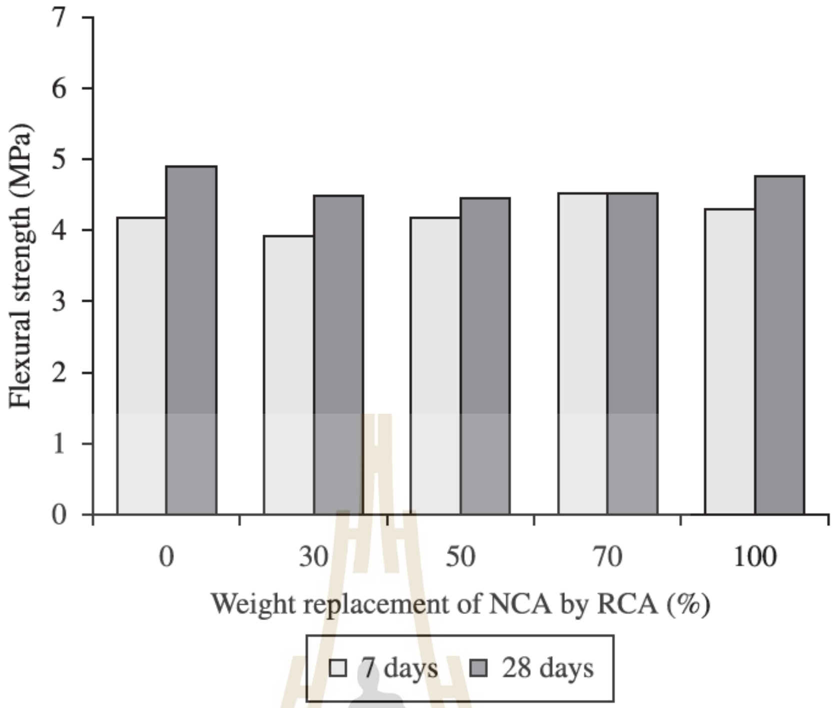


Figure 2.4 Replacement of RCA in flexural strength (Safiuddin et al., 2011).

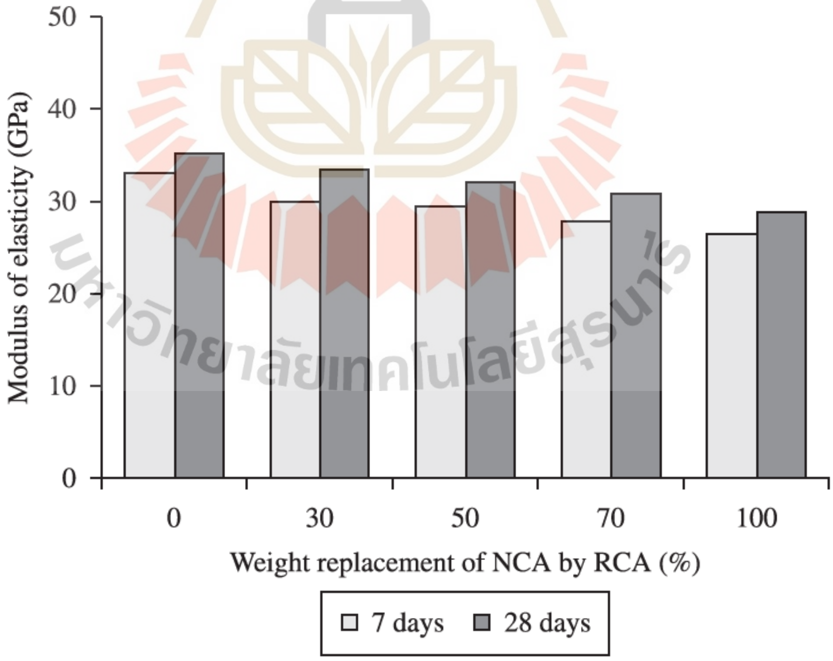


Figure 2.5 Replacement of RCA in modulus of elasticity (Safiuddin et al., 2011).

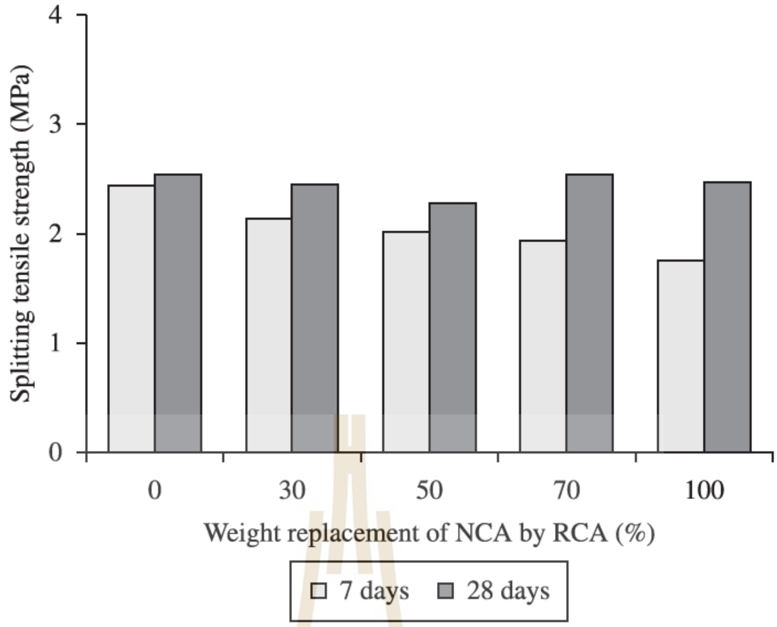


Figure 2.6 Replacement of RCA in splitting tensile strength (Safiuddin et al., 2011).

Therefore, RCA can be considered as an alternative material to replace NCA for concrete application as several studies has been investigated in the same result of reducing a minor amount of compressive strength, compressive strength, and split tensile strength (Nagataki et al., 2000; Shayan et al., 2003).

2.3 Hemp Fiber Treatment

Fiber reinforced concrete has been used in civil engineering for several years to improve the ductility and reduction of the volume of concrete. Synthetic fibers such as carbon, glass or aramid fiber are used in some applications because of the high cost. Of course, synthetic fibers provide higher tensile strength and modulus of elasticity but exchange with the energy consumption and environmental pollutions. Thus, the natural fibers such as hemp, jute and sisal have been a focus point for the alternative which several studies stated that natural fibers had low density, great tensile strength and modulus of elasticity according to cellulose contains and can be considered as reinforcer of polymeric matrix (Bledzki and Gassan, 1999). Due to affordable price and eco-friendly, the are some disadvantages that come with interaction of fiber surface to concrete matrix and the impurity attached to the surface. So, the treatment process has instigated which sodium hydroxide (NaOH) is found to be effective and cheap. NaOH has roles to wash the surface and improve the mechanical properties, modulus of elasticity and tensile strength (Sharifa and Ansell, 2004). To activate the alkaline treatment, 6% of NaOH solution was prepared and maintained at room temperature and saturated for 48 hours and cleaned with distill water then air-dry. The samples were investigated with scanning electron microscope (SEM) to see the surface of the fiber by 500 times zoom in from Poletanovic et al. in figure 2.7.

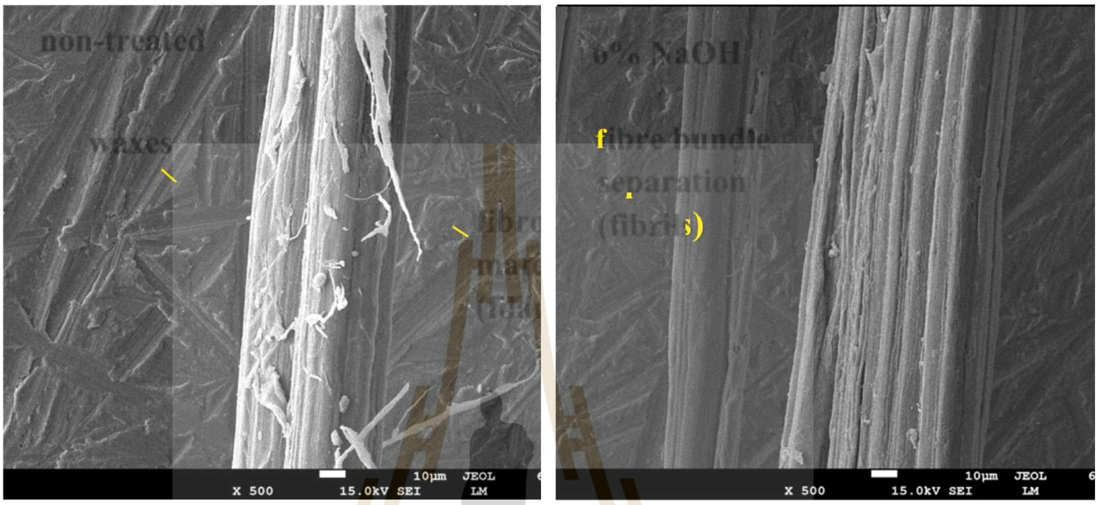


Figure 2.7 SEM of untreated hemp fiber and 6% NaOH treatment hemp fiber (Peletanovic et al. 2021).

Without treatment, the surface of hemp fiber attached with waxes and dusts which made the hemp fiber in form of smooth surface contact, whereas after treatment the waxes and filaments were removed. Thus, the hemp fiber was left without interruption and resulted remain with pure fiber.

2.4 Previous Studies on Hemp Fiber Reinforced Concrete

Different types of fibers such as steel, glass, natural and synthetic fibers have been used to study to reinforced with concrete in the last decades to improve the cracking performance on stress transferred (Quan and Stroeven, 2000; Akay and Tasdemir, 2012; Ponikiewski and Katzer, 2014; Su and Lin, 2017) but adding fibers to concrete resulted in effecting the compressive strength, flexural strength and mode of failure against its brittleness (Barros et al., 2005; Usman et al., 2020). Krishna and Rao in 2021 conducted an experiment by using polyester fiber reinforced concrete as a rigid pavement and resulted in improvement of compressive strength, flexural strength and splitting tensile strength by adding 0.3% fiber content and assisted to reduced 20 % of thickness of pavement.

Hemp concretes were interested by several researchers and studied to save natural resources. Lightweight hemp concrete was used in walls, slabs and plasters for timber buildings and repaired work in France since 1990 (Allin, 2005). Gencel et al. (2021) observed the behavior of hemp fibers reinforced with foam and fly ash which gave an increment of compressive strength when using higher foam content and for long term strength was improved when mixing with low foam content and 30% of fly ash. Furthermore, hemp fiber with 10 % of fly ash can strengthen the flexural strength of foam concrete. Comak et al. (2018) tested various length of short hemp fiber with different hemp fiber content for investigated the characteristic of cement-based mortar. In addition, mixing with 2-3% of 12 mm hemp fiber length improved compressive strength, flexural strength, and splitting tensile strength. The resulted was tested by Sedan et al.(2008) showed that treated hemp fiber with NaOH increased surface roughness and hemp FRC increase the flexural strength at acceptable amount and in contrast to modulus of elasticity that decreased. Another study case proposed by using 0.5% of hemp fiber content by weight of concrete and found that 25 % of flexural strength was improved compared to normal concrete (Ramadevi and Shri, 2004). However, Li et al. (2004) stated that at optimum hemp fiber content increased 4% of compressive strength, 9% of flexural strength, and 114 % of flexural toughness compared to normal concrete. Significantly, length of the hemp fiber did not have much effect to the concrete properties but alkali presented on hemp fiber produced good results for HFRC but exchanged with reduction of compressive strength and modulus of elasticity where modulus of rupture and tensile strength were increased notably (Awwad et al., 2012; Awwad et al., 2013).

2.5 Knowledge Gap and Proposed Research on Hemp Fiber

Sedan et al. (2018) stated that during testing the flexural strength, fiber pullout was the problems which effected the load transferred process. Therefore, previous studies revealed that the difference of HFRC strength were based on mix design.

Reinforced concrete with hemp fiber can result in ductile behavior and produce great energy absorption but applications of HFRC have been applied to beam and column which required modulus of elasticity, compressive strength, and flexural strength. One of the most important infrastructures like pavement requires to observe a long-term post-crack behavior which relates to flexural strength, flexural toughness, and toughness index that have positive contribution to have a long service life. Pavement is designed to support dynamic loads which flexural fatigue test will require for hemp FRC. Natural resources of coarse aggregate such as limestone is not eco-friendly to environmental which to maintain the sustainability pavement, recycled concrete aggregate will use to replace limestone to study with hemp fiber.

The primary parameter of concrete pavement design is based on the fatigue resistance which causes the distress to pavement. Large number of cyclic loads as induced by traffic can reduce the performance of concrete propagation cracks, deteriorating the elastic properties , increasing the fatigue fracture toughness (Perdikaris et al., 1986; Matsumoto, 1998; Lee and Barr, 2004) and eventually leading to the brittle failure of the material. The internal progressive damage of plain concrete occurs under repeated loads to form crack and ultimately fail due to flexural fatigue (Maitra et al., 2014). In design progression, fiber can resist the crack propagation which will increase the endurance life of the materials and contribute to a more ductile behavior (Chang and Chai, 1995; Rossi and Parant, 2008). According to the American Association for State Highway and Transportation Officials (AASHTO) was developed the performance prediction of concrete pavement in late 1950s which studied on the behavior and several tested data to create the empirical methods but did not include the fatigue performance that can cause the failure to the pavement. Therefore, the traditional design methods are mostly over-designing the strength to ensure the durability of pavement but did not address the failure of fatigue (Sabih and Tarefder, 2018). Thus, the mechanistic-empirical pavement design guide (MEPDG) was introduced in 2004 by AASHTO in cooperation with the National Cooperative Highway Research Program (NCHRP) and the Federal Highway Administration (FHWA). Since the MEPDG is based on the behavior and materials properties, this will have a potential to reduce the degree of uncertainty in the design steps which combined with realistic criteria for design the level of distress. For this reason, there will have more certainty of design and materials which significantly leads to reduce the maintenance process and rehabilitation activities (Ceylan et al., 2008). That being the case for this research to evaluate the fatigue performance and develop MEPDG method of hemp fiber reinforced concrete pavement with RCA.

CHAPTER III

RESERCH METHODOLOGY

3.1 Materials

3.1.1 Cement

Ordinary Portland cement was used for fresh concrete mixing, which had the chemical composition examined from the product manufacturer as Table 3.1. Portland cement type I had the specific gravity of 3.14.

Table 3.1 Chemical composition of ordinary Portland cement (OPC).

Component (%)	*OPC*
Silicon dioxide (SiO_2)	20.9
Aluminum oxide (Al_2O_3)	4.7
Iron oxide (Fe_2O_3)	3.4
Calcium oxide (CaO)	65.4
Magnesium oxide (MgO)	1.2
Sulfur trioxide (SO_3)	2.7
Loss on ignition (LOI)	0.9

3.1.2 Natural Rubber Latex

The properties of natural rubber latex are obtained from the Rubber Authority of Thailand, which has 52% dry rubber and 48% water and water-soluble com-ponents. The pH was tested to ensure the acidity content in the rubber controlled the prop-erty for the other tests, which equaled 10.4.

3.1.3 Fine, Coarse Aggregate, Crumb Rubber and PET

Crushed limestone and tested Portland Cement Concrete from ready-mix plants (PCC) were used as natural coarse aggregate (NCA) and recycled concrete aggregate (RCA), respectively, with maximum size aggregate of 20 mm and following by river sand as fine aggregate which had the basic physical and engineering properties in summary in Table 3.2. According to ASTM C33, there were upper and lower boundary to be controlled of particle size distribution in other to avoid the error of sizing of particles of fine aggregate and coarse aggregate (crushed limestone and river sand) that are shown in Figure 3.1 for NCA and RCA and Figure 3.2 for waste polymer concrete using NRL with the combination with sand in the ratio of 50:50.

Table 3.2 Basic physical and engineering properties of fine, coarse aggregate, PET and Crumb Rubber.

Properties	Value	
Coarse aggregate	*NCA*	*RCA*
Maximum size aggregate (mm)	19	19
Saturated surface dry specific gravity	2.77	2.45
Dry specific gravity	2.47	2.28
Dry rodded density ($kg.m^{-3}$)	1634	1398
Absorption (%)	1.86	2.24
Moisture content (%)	0.98	1.59
Abrasion loss (%)	22.4	30.7
Fine aggregate		
Saturated surface dry specific gravity	2.62	
Dry specific gravity	2.60	
Percentage of voids (%)	38.24	
Dry unit density ($kg.m^{-3}$)	1613	
Absorption (%)	0.74	
Moisture content (%)	0.46	
Fineness modulus	2.75	
Waste Polymer	PET	Crumb Rubber
Appearance	Round and Smooth	Black and Rough
Particle size (mm)	9 – 10	2-3
Dry specific gravity	1.20	1.02
Water absorption (%)	0.02	1.05
Melting point (°C)	255	196

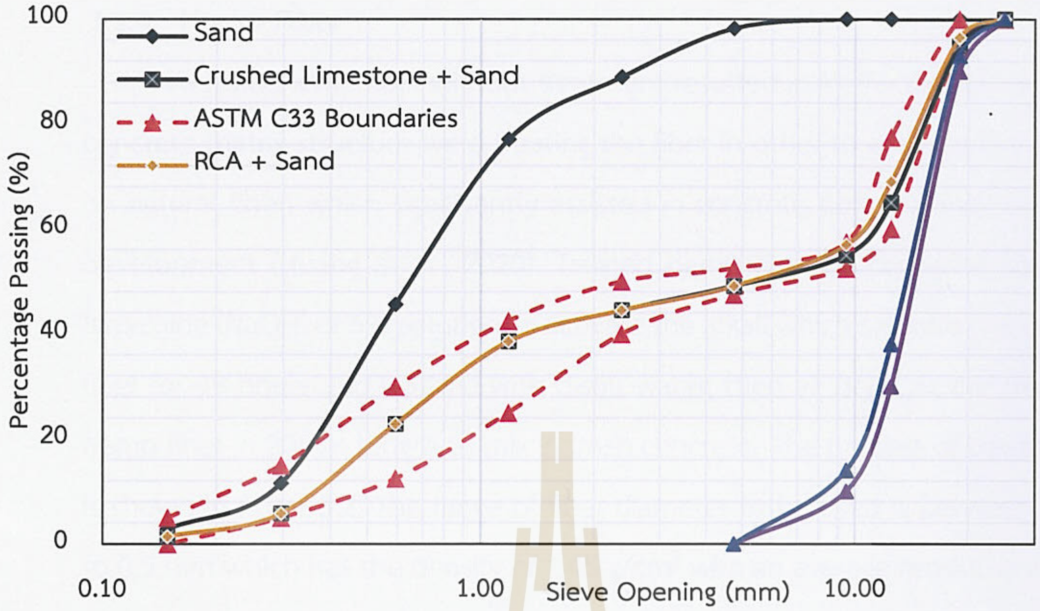


Figure 3.1 Particle size distributions of sand, crushed limestone, recycled concrete aggregate, crushed limestone + sand, and recycled concrete aggregate + sand.

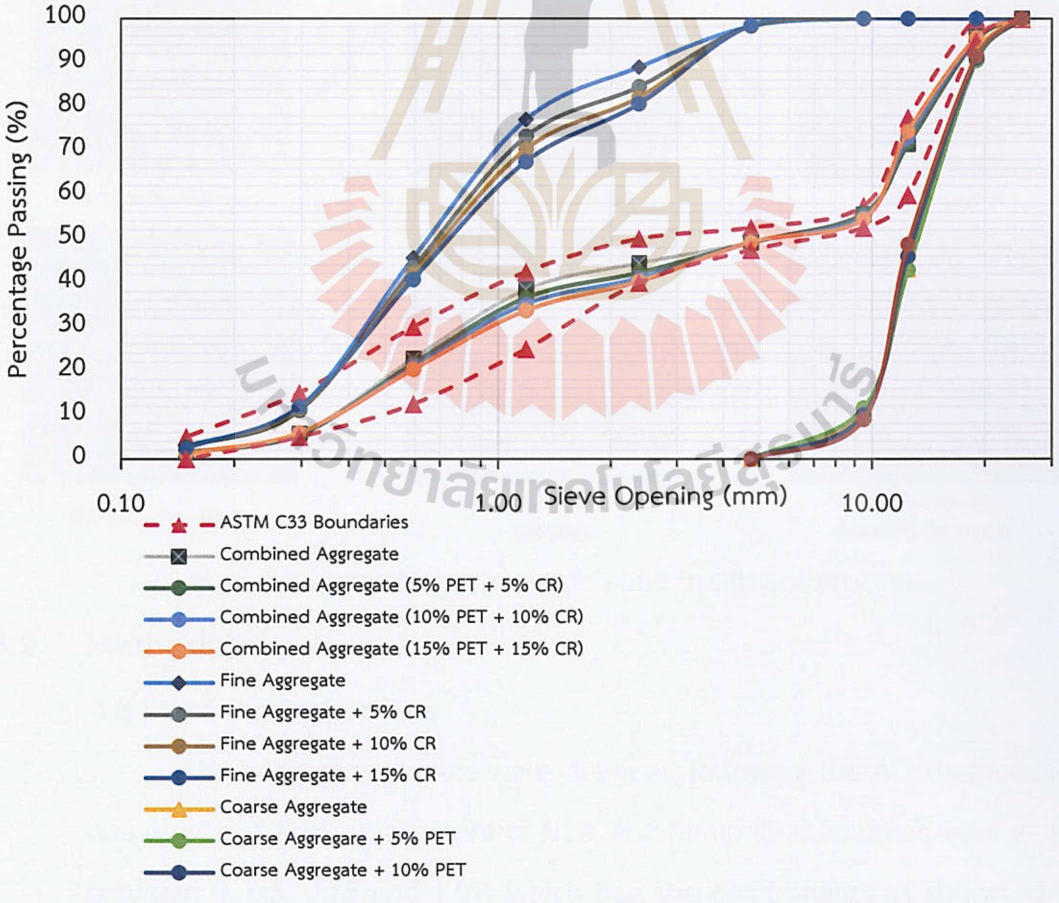


Figure3.2 Particle size distributions of sand, crushed limestone, and waste polymer.

3.1.4 Hemp Fiber

Natural hemp fiber without treatment resulted in ineffective bonding of concrete matrix structure were treating the fiber in other to activate the alkali on natural fiber, which significantly assisted in concrete bonding and strength development (Huang et al., 2020). Treated hemp fiber by preparing sodium hydroxide (NaOH) of 6% solution to activate the alkali which saturate the hemp fiber for 48 hours and washed with distill water, then air dry. Cut the treated hemp fiber in 20mm length to mix in fresh concrete. The process of treatment is shown in figure 3.2. The range of fiber diameter to be used is between 0.03 to 0.5 mm which has the density of 1.45 g/cm^3 with an average tensile strength of 600 MPa.

Figure 3.3 Hemp fiber preparation and treatment process.

3.2 Methodology

3.2.1 Mixing Proportions

The concrete samples were designed following the ACI method, RCA was used as 100% replacement of NCA, and hemp fiber volumes were varying between 0, 0.5, 0.75 and 1.0% which had the components as shown in the table 3.3 below with fresh concrete during mixing in figure 3.3.

Table 3.3 Mixing proportion of waste polymer using NRL.

Specimen	w/c	Cement	Water	F.A.(kg.m^{-3})		C.A. (kg.m^{-3})		NRL 0.58%)
		(kg.m^{-3})	(kg.m^{-3})	Sand	C.R.	NCA	PET	(kg.m^{-3})
Control	0.5	385	192.5	745	0	1052	0	0.0
NRL	0.5	385	191.4	745	0	1052	0	2.23
NRL10WP	0.5	385	191.4	708	37	999	53	2.23
NRL20WP	0.5	385	191.4	671	75	947	105	2.23
NRL30WP	0.5	385	191.4	633	112	894	158	2.23

Natural Rubber Latex, NRL = ((r/c)/100) C

Water Content in NRL, WNRL = 0.48 NRL

Total Water Used, Wt = WD - WNRL

Where r/c = rubber to cement ratio (%), C = cement (kg), WNRL (kg), and Wt (kg).

Table 3.4 Mixing proportion of hemp fiber reinforced concrete.

Specimen	w/c	Cement ($kg.m^{-3}$)	Water ($kg.m^{-3}$)	Fine aggregate ($kg.m^{-3}$)	Coarse aggregate ($kg.m^{-3}$)	Hemp fiber Vol. (%)	Hemp fiber Weight (kg)	MRWR ($kg.m^{-3}$)
Natural coarse aggregate								
NCA-0.0H-FRC	0.5	370	185	812	1039	0.00	0.00	0.0
NCA-0.5H-FRC	0.5	370	185	812	1039	0.50	12.03	3.7
NCA-0.75H-FRC	0.5	370	185	812	1039	0.75	18.05	3.7
NCA-1.0H-FRC	0.5	370	185	812	1039	1.00	24.06	3.7
Recycled concrete aggregate								
RCA-0.0H-FRC	0.5	370	185	812	1039	0.00	0.00	0.0
RCA-0.5H-FRC	0.5	370	185	812	1039	0.50	12.03	3.7
RCA-0.75H-FRC	0.5	370	185	812	1039	0.75	18.05	3.7
RCA-1.0H-FRC	0.5	370	185	812	1039	1.00	24.06	3.7

(a) (b) (c)

Figure 3.4 Hemp Fiber Concrete Mixing: (a) mortar with hemp fiber (b) hemp fiber concrete (c) slump test.

3.2.2 Concrete Setting Time of HFRC

A constant water to cement ratio (w/c) ratios at 0.5 with two differences type of coarse aggregate such as NCA and RCA were tested to indicate the initial and final setting time of 4 different of hemp fiber and cement ratios, which were 0, 0.5, 0.75 and 1.0 by the cement weight using Penetration Resistance methods in accordance with ASTM C403 as shown in Figure 3.4. The concrete samples were mixed in accordance with mixing proportions table 5. The samples were sieved through sieve N4 to get rid of the aggregates. Concrete particles lower than N4 were cast in cubic mold and left top gaps about half of centimeter from the mold to avoid the splashing during penetration. The samples were prepared at room temperature and flattened the surface. Different resistance plungers were used to convert into resistance strength (MPa) and plotted into the graph. At 3.5MPa and 27.6 MPa indicated initial and final setting time of the concrete respectively.

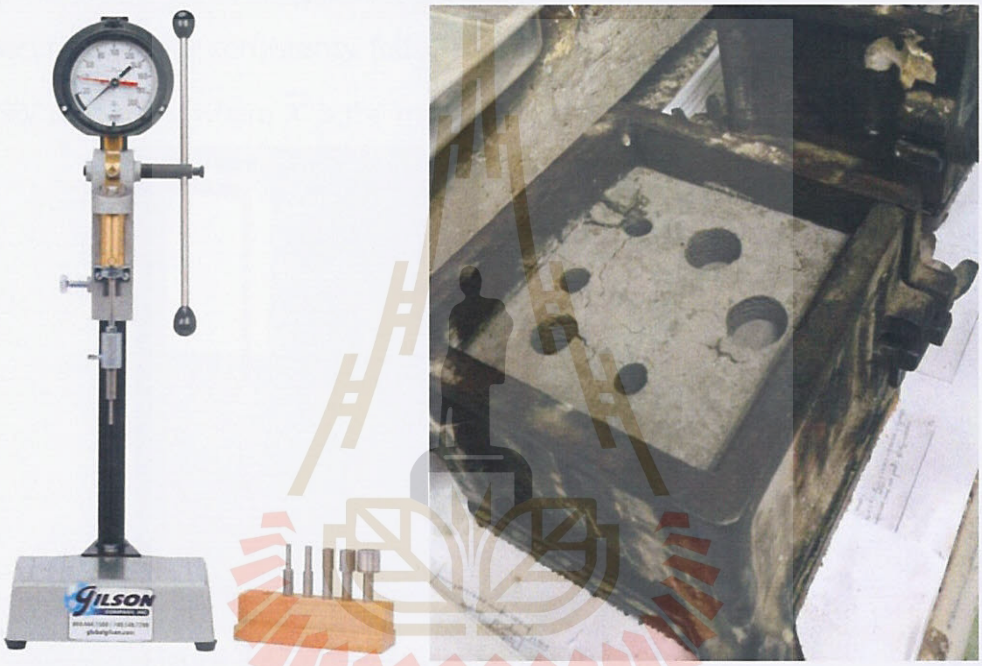


Figure 3.5 Penetration Resistance Apparatus and Concrete Sample.

3.2.3 Compressive and Flexural Tests

The fresh concrete was prepared by using a rotary drum mixer following the ASTM C192. For compression, cubic mold was cast in the dimension of 150×150×150 mm and prismatic mold of 150×150×600 mm for the flexural strength test. Casting process was divided into 3 layers equally and compacted each layer for 25 blows by using standard tamping rod and trimming the surface, then waited for 24 hours at room temperature to remold and continued to water curing process in the water tank with the temperature at 27 ± 2 degree Celsius. At the day 7 and 28, the specimens were tested in compression by following ASTM C39 and AASHTO T97 using testing machine as shown in figure 3.5 and 3.6, third-point load test for flexural strength and calculated the strength by the equation below:

Flexural strength, $f_f = \frac{PL}{bd^2}$ (1)

Where P is the maximum applied load; L is a support length; b is the average width of beam specimen and d is the average depth of the sample.

The tested data were analyzed in the mean value of triad specimens within the same testing condition in compression and flexural strength to secure the data consistency following with low mean standard deviation, SD (SD/ $\overline{x}$ < 10 %, where $\overline{x}$ is the mean strength value).

Figure 3.6 Compressive Strength Test Machine.

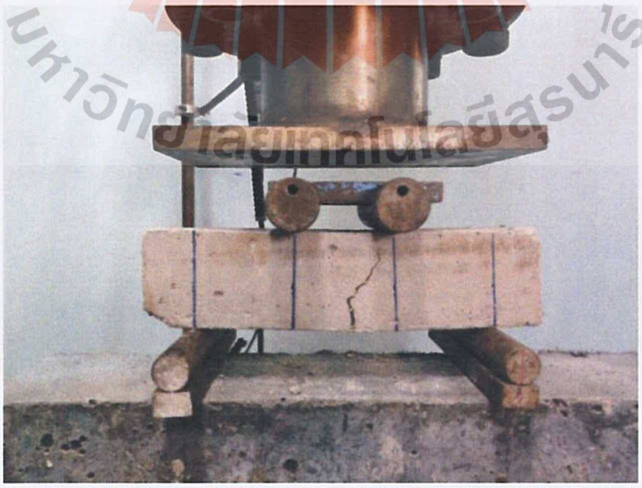


Figure 3.7 Flexural Strength Test Machine.

3.2.4 Flexural Fatigue Test

Three-point load fatigue test was used to examine the specimen that passed the requirement of Department of Highway Thailand of both compression and flexural strength. Using 500 kN electro-hydraulic servo testing machine (Figure 3.7) to indicate the behavior with autonomous data recorder accordance to modulus of resilience. A haversine loading pulse of vertical loading with the loading frequency of 5 Hz with various stress ratio (SR) such as 60%, 70% and 80% of flexural strength to obtain the number of cycles which simulate the speed of vehicular anticipated on low to medium volume of the pavement. The stress ratio can be calculated from the equation below:

$$SR = \frac{\sigma}{f_f} \tag{2}$$

Where σ is the applied flexural stress; f_f is the failure strength of flexural test.

Figure 3.8 Flexural Fatigue Test Machine.

3.2.4 SEM Analysis

The effect from hemp fiber of bonding in concrete matrix is to be considered on both flexural and compressive strength were investigated using a scanning electron microscope (SEM) attached with an energy dispersive X-ray detector analysis that well known as EDX (figure 3.8). The sample elements of 0.0%, 0.5% and 1,0% for both NCA and RCA from the testing were kept for SEM and EDX analysis. Freezing and drying methods were carried out to avoid the hydration process of selected fragments and coat with gold prior to for SEM analysis. Observation points were chosen to analyze by EDX corresponding directly to the SEM morphological detection at 200 times of magnification for concrete samples at 28 days and 100 times for hemp fiber.

Figure 3.9 Scanning Electron Microscopy Machine.

CHAPTER IV
RESULTS AND DISCUSSIONS

4.1 Concrete Setting Time of HFRC

In figures 4.1, 4.2 and 4.3, the initial and final setting time was shown in the relationship between various hemp fiber contains and time in minute. The mixture of RCA and NCA were compared to observe the differences behavior of concrete hydration. Reinforcing higher volume of hemp fiber into concrete was reduced both initial and final setting time for RCA and NCA. At the stress of sample of 500 pound per square inch, the initial setting time were determined equal to 205, 182, 160, 145 minutes for NCA and RCA of 210, 188, 170, 150 minutes with 0, 0.5, 0.75, and 1 % hemp fiber reinforcement, respectively. As well as the final setting time was investigated when the stress reached 4000 pound per square inch which equal to 376, 342, 311, and 282 minutes for NCA and 370, 340, 332, 280 minutes for RCA with 0, 0.5, 0.75, and 1 % hemp fiber reinforcement, respectively. NCA and RCA samples had similar behavior which the differences were not more than 10 minutes. Whereas, reinforcing 0.5% of hemp fiber approximately 20 minutes were reduced in initial setting time and final setting time for 30 minutes compared to without reinforcing. Moreover, 0.75% of hemp fiber resulted in decreasing the initial setting time of roughly 40 minutes and 50 minutes for final setting time compared to 0% of reinforcement. Lastly, an hour reduction of initial setting time and 90 minutes for final setting were observed at 1.0% of hemp fiber reinforcement in contrast with controlled sample.

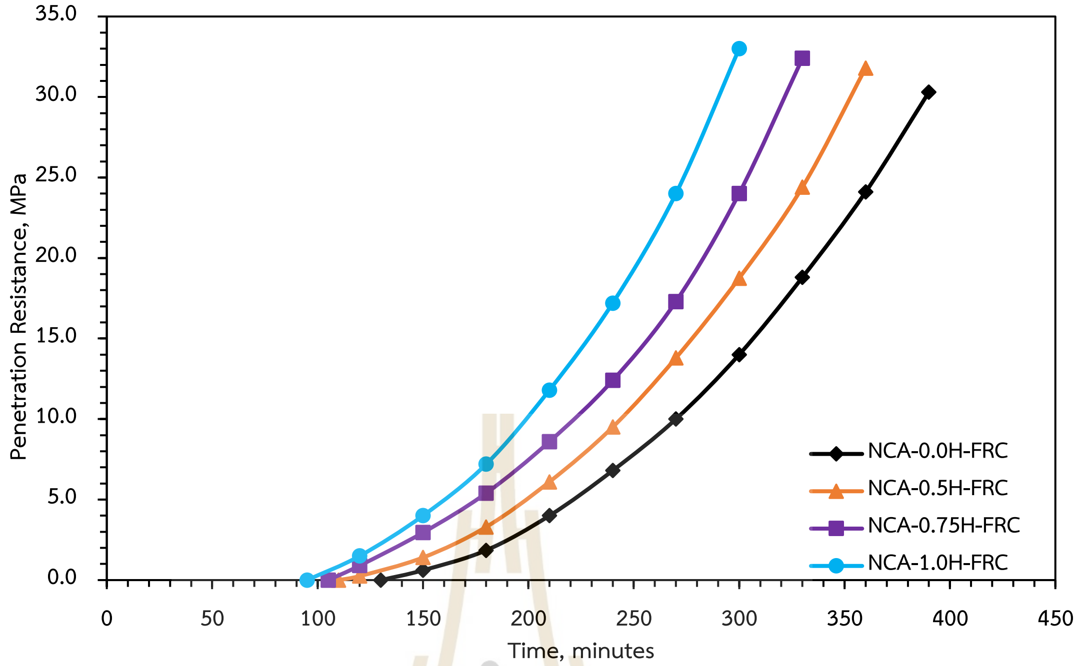


Figure 4.1 Curve of Initial and final setting time of HFRC using NCA.

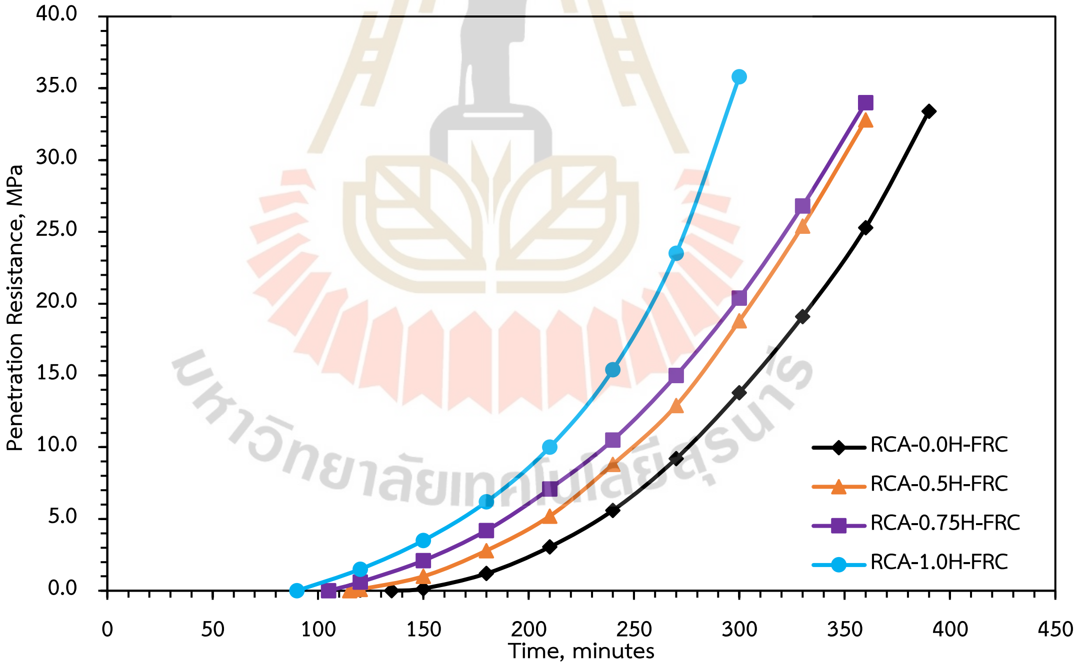


Figure 4.2 Curve of Initial and final setting time of HFRC using RCA.

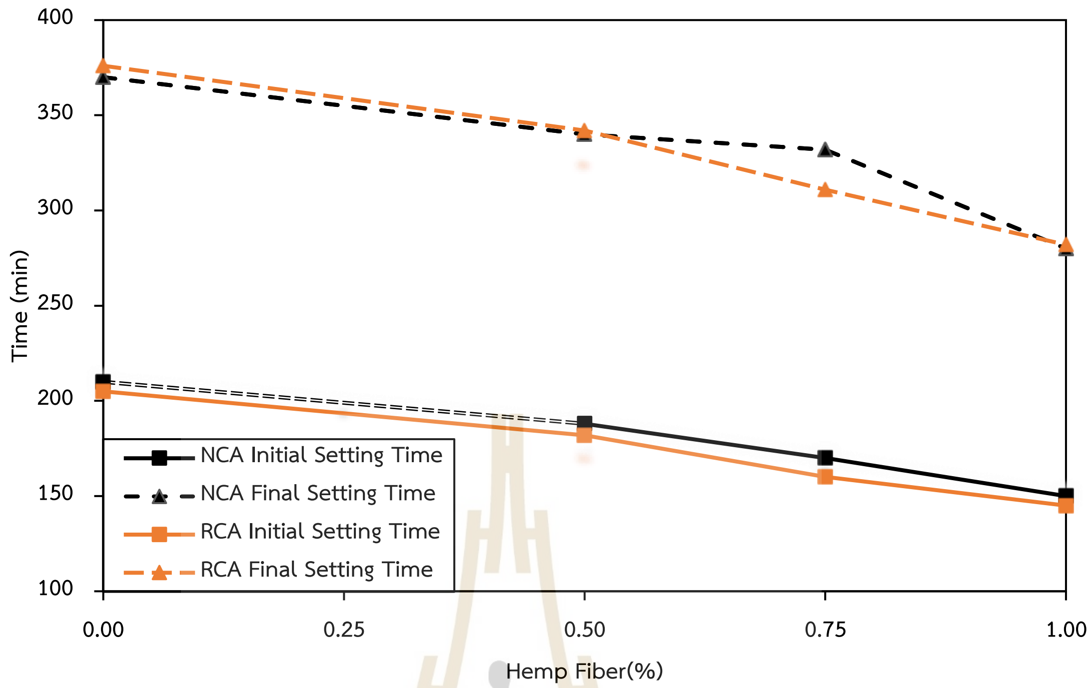


Figure 4.3 Initial and final setting time of HFRC.

4.2 Compressive Strength

The test results of cubic compressive strength development at 7 and 28 days are shown in Figure 4.4, indicating an increase in compressive strength ranging from 60% to 70% at 7 days compared to 28 days for both RCA and NCA, which aligns with the expected behavior of concrete. At 28 days, the control sample, named NCA-0.0H-FRC, without reinforcement with hemp fiber, and using NCA commonly used in the civil engineering field, reached a strength of 39.54 MPa. After adding 0.5% hemp fiber by volume weight, NCA-0.5H-FRC showed a 7.3% reduction counted as 36.65MPa in strength. Further addition of 0.75% hemp fiber resulted in a significant decrease to 31.42 MPa, accounting for 20.5% of NCA-0.75H-FRC. Similarly, NCA-1.0H-FRC experienced a 36.1% drop in strength with 1.0% hemp fiber content. In addition to NCA, recycled concrete aggregate also exhibited notable strength at 28 days, with RCA-0.0H-FRC providing a compressive strength of 37.90 MPa. Furthermore, RCA-0.5H-FRC, with 0.5% hemp fiber, reduced strength by 7.3% as 35.14MPa. Similarly, with 0.75% hemp fiber incorporation, RCA-0.75H-FRC experienced a remarkable 23.3% reduction and 29.14MPa in strength. Likewise, with 1.0% hemp fiber reinforcement, RCA-1.0H-FRC effectively diminished to 22.42MPa strength by 41.2%. In addition to peak performance, Figures 4.5 and 4.6 illustrate the energy absorption of hemp fiber-reinforced concrete, showing differences in breaking points. Initially, without hemp fiber, the concrete exhibited no strain extension, behaving as a brittle material. However, as the percentage of hemp fiber increased, HFRC demonstrated increased elongation, introducing ductility to both NCA and RCA. On the other hand, DH-S 309/2544 specifies a compressive strength requirement of higher than 32.5 MPa for pavement construction, indicating unsatisfactory use of 0.75% and 1.0% hemp fiber-reinforced concrete for both RCA and NCA. Therefore, while HFRC using NCA achieved higher compressive strength than RCA, it remained within an acceptable range for both materials. Consequently, HFRC will continue utilizing only 0.5% hemp fiber reinforcement to meet the compressive strength requirement. Figures 4.7 and 4.8 below show compressive failure of hemp fiber reinforced concrete using NCA and RCA. Without help fiber, mode of failure of concrete was semi-explosive which cement mortar was broken into small pieces from specimen with a lot of cracking. After adding hemp fiber, the mode of failure changed to non-explosive which occurred by the presence of fiber to help holding the concrete matrix together. Therefore, in concrete pavement application, this is also one of the advantages to reduce the cracking of the road and improve the energy absorption in concrete.

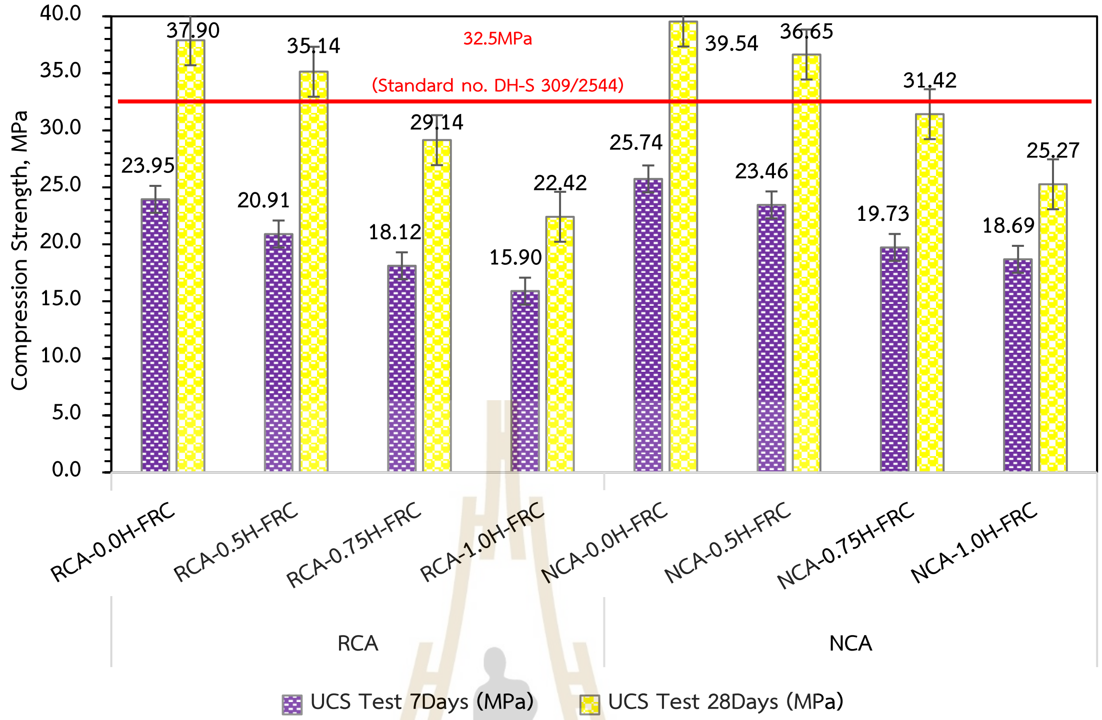
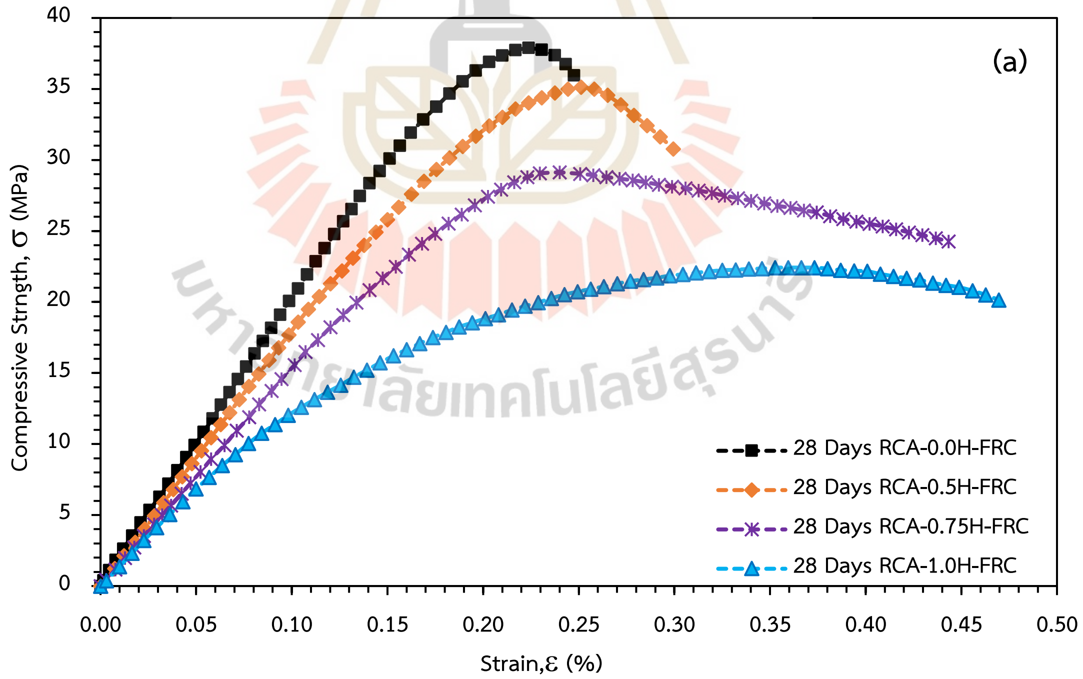


Figure 4.4 Strength development of compressive strength using NCA and RCA.



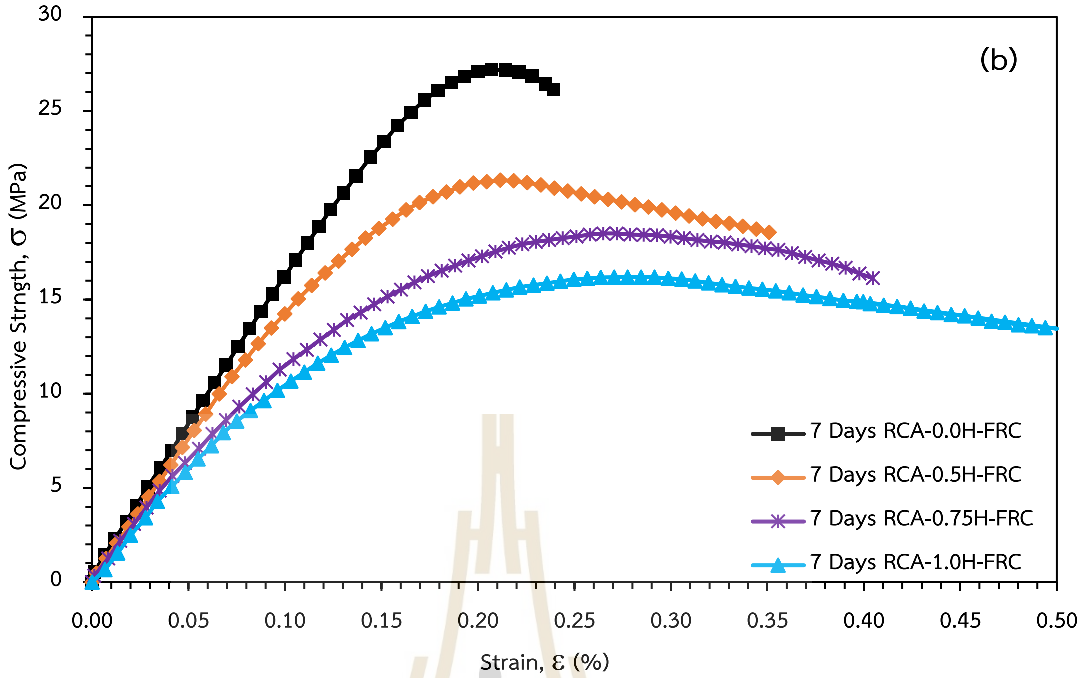
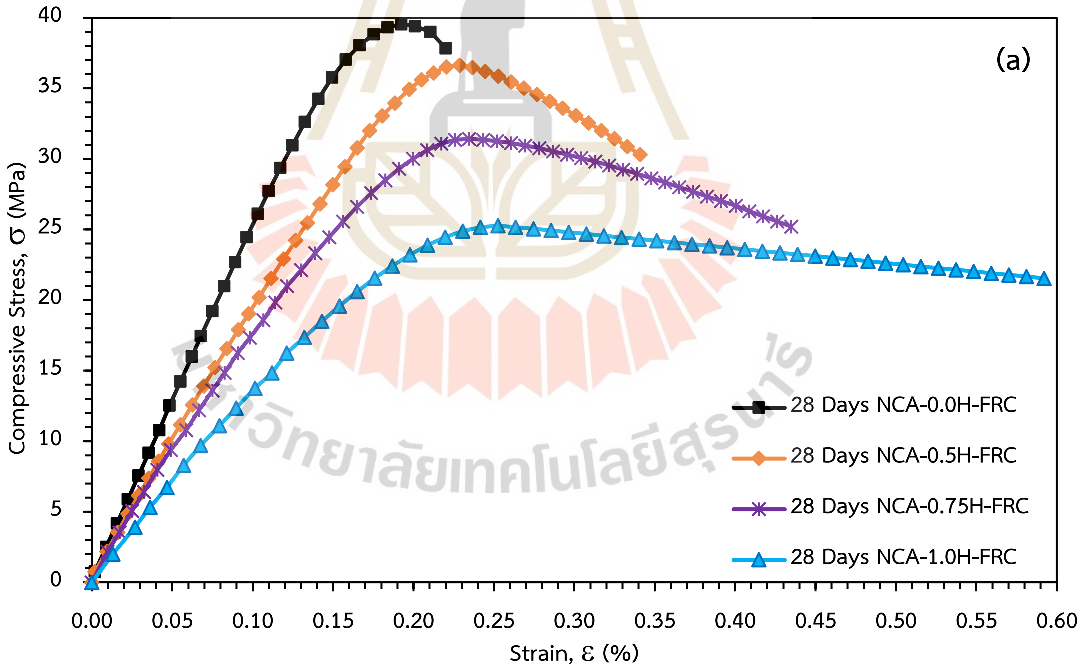


Figure 4.5 Stress-stain curve at (a) 28-days and (b) 7-days using RCA.



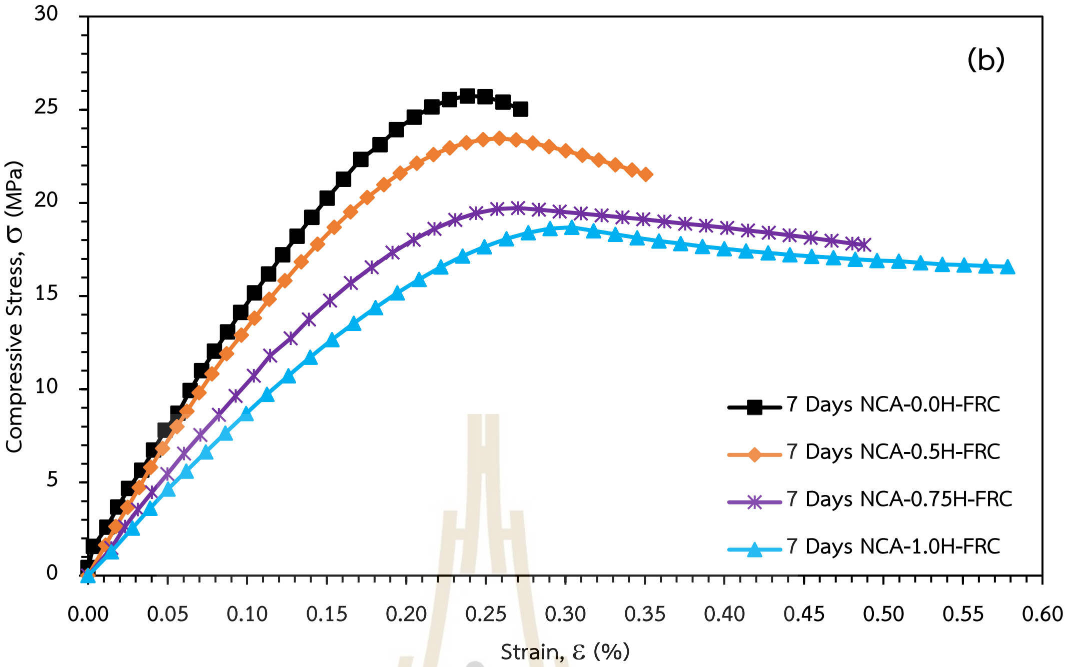
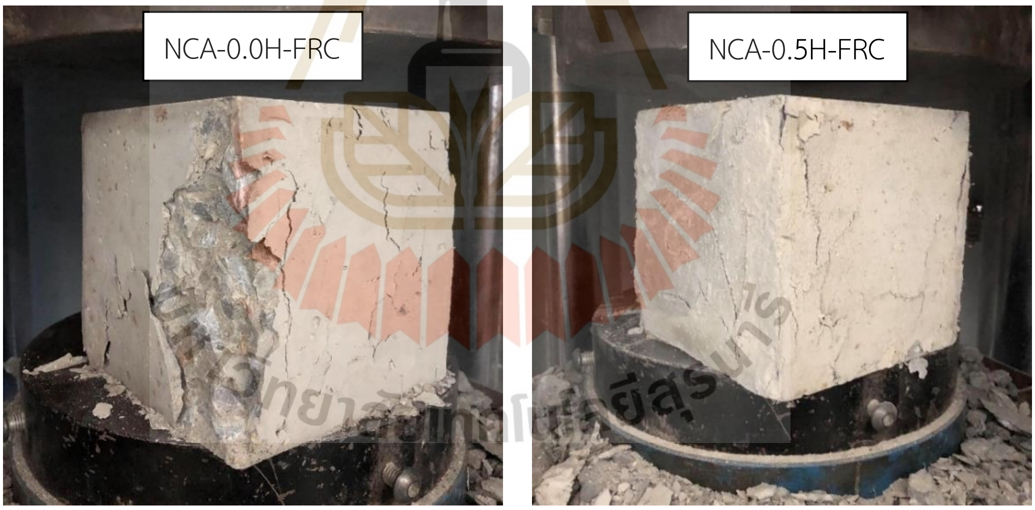


Figure 4.6 Stress-stain curve at (a) 28-days and (b) 7-days using NCA.



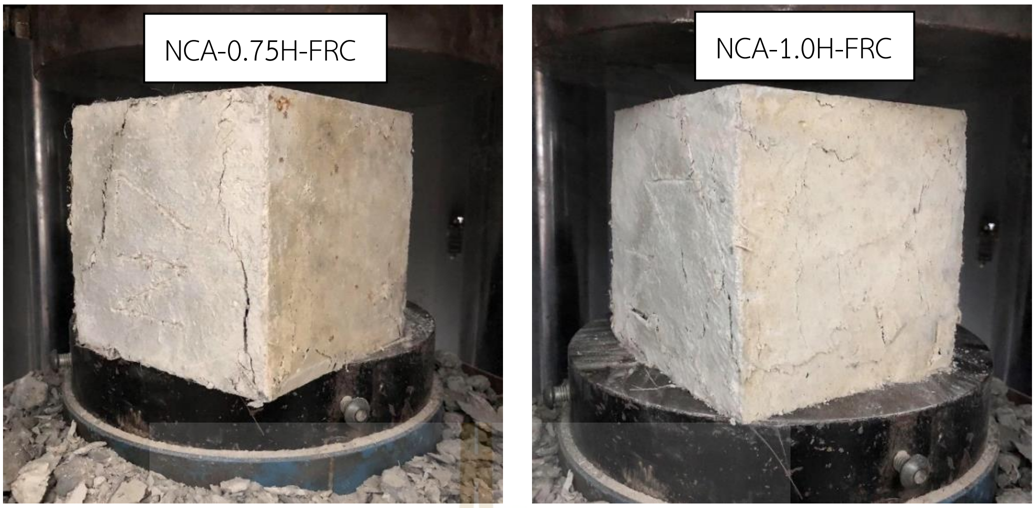


Figure 4.7 Compressive failure of hemp fiber reinforced concrete using NCA.

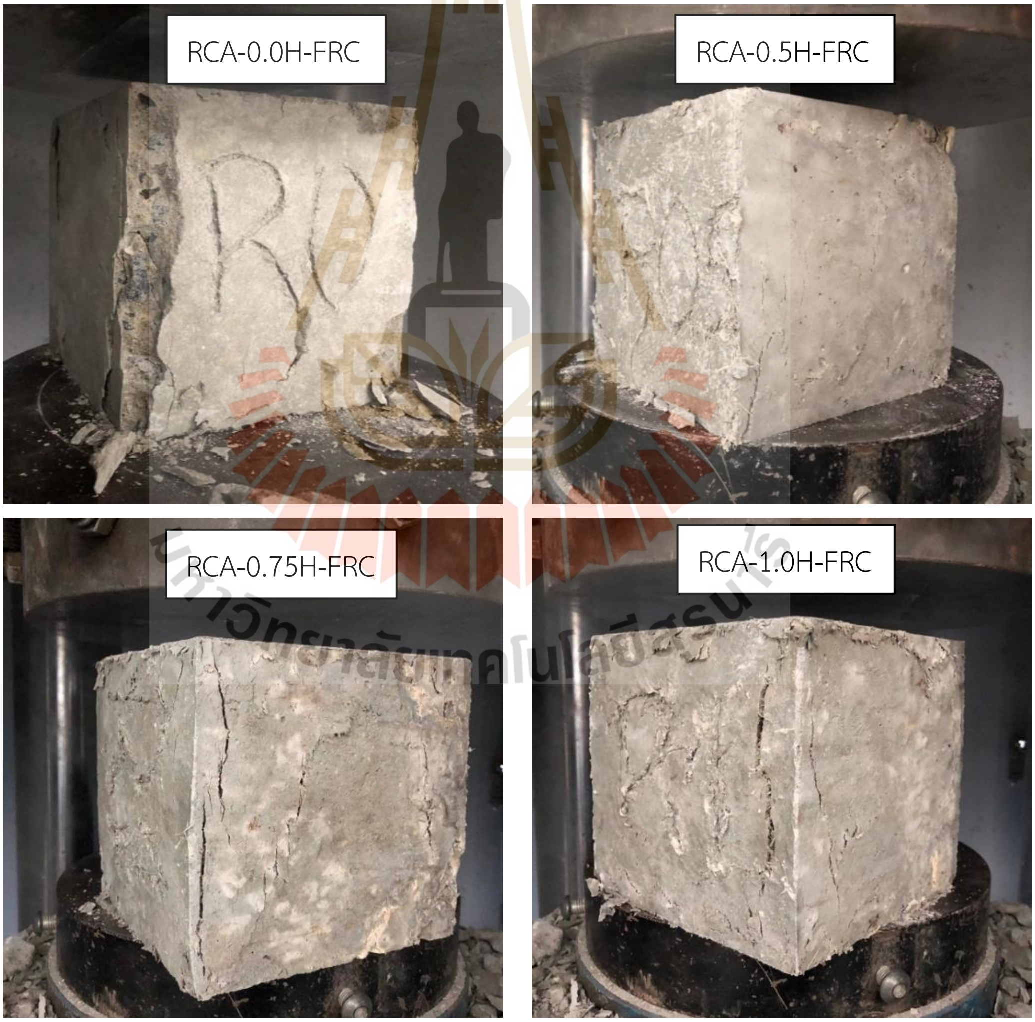


Figure 4.8 Compressive failure of hemp fiber reinforced concrete using RCA.

The compressive strengths of the studied samples cured at 7, 14, and 28 days are shown in Figure 4.9. The solid red line demonstrates the minimum 28-day compressive strength requirement (fc ≥ 32 MPa) for concrete pavement specified by the Department of Highways (DOH), Thailand (DoH, 1996). For normal concrete (controlled sample), Increment of compressive strength was in relation with time of curing (compressive strength of 27.6, 34.3, and 38.8 MPa at 7, 14, and 28 days, respectively). As expected, when added NRL additive was to the concrete, utilization of NRL in concrete produced a decreasing of compressive strength compared to control sample, which was similar to the previous research (Yaowarat et al., 2021; Suddeepong et al., 2022). The NRL-modified concrete had a compressive strength of 24.6, 29.6, and 34.3 MPa at 7, 14, and 28 days. The compressive strength of the NRL-modified concrete with waste aggregate replacements decreased with increasing aggregate replacement ratios and was less than regular concrete and NRL-modified concrete, respectively. This result was consistent with earlier investigations on the effects of used PET bottles and crumb rubber aggregates on the hardened qualities of concrete (Islam et al., 2016; Frigione, 2010; Guo, 2017). However, Compressive strength at 28 days of NRL10WP (NRL-modified concrete with 5% PET + 5% crumb rubber aggregate) satisfied the minimal strength requirements to use as concrete pavement designated by DOHs, Thailand. The compressive strength of NRL10WP was 21.9 MPa, 28.77 MPa, and 32.5 MPa at 7, 14, and 28 days, respectively, which was found to reduce the strength by 8.3% compared to the NRL-modified concrete. The compressive strength of NRL20WP was 15.46, 24.48, and 29.11 MPa at 7, 14, and 28 days, respectively, which was approximately 15% in strength reduction when compared to the NRL-modified concrete. The compressive strength was found to be remarkably reduced when 30% of waste aggregate replacement in the NRL-modified concrete. The compressive strength of NRL30WP was 13.6, 22.3, and 24.5 MPa at 7, 14, and 28 days, respectively. The 28-day compressive strength of NRL30WP indicated 28.5% and 36.9% in strength reduction when compared to the NRL-modified concrete and normal concrete, respectively.

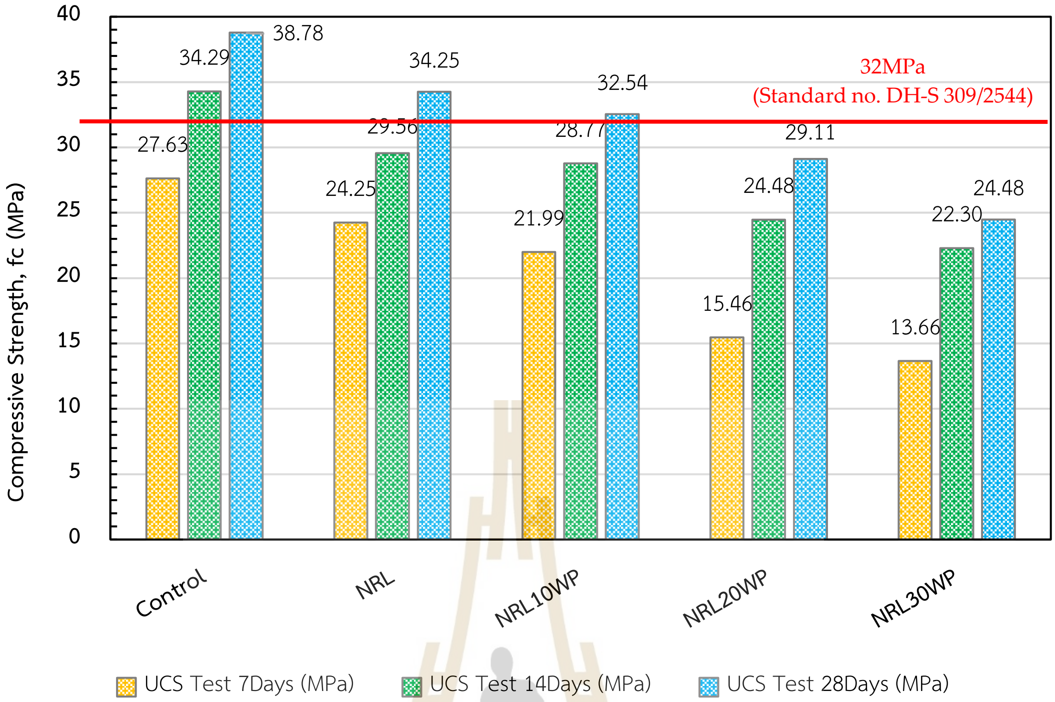


Figure 4.9 Strength development of compressive strength of waste polymer concrete using NRL.

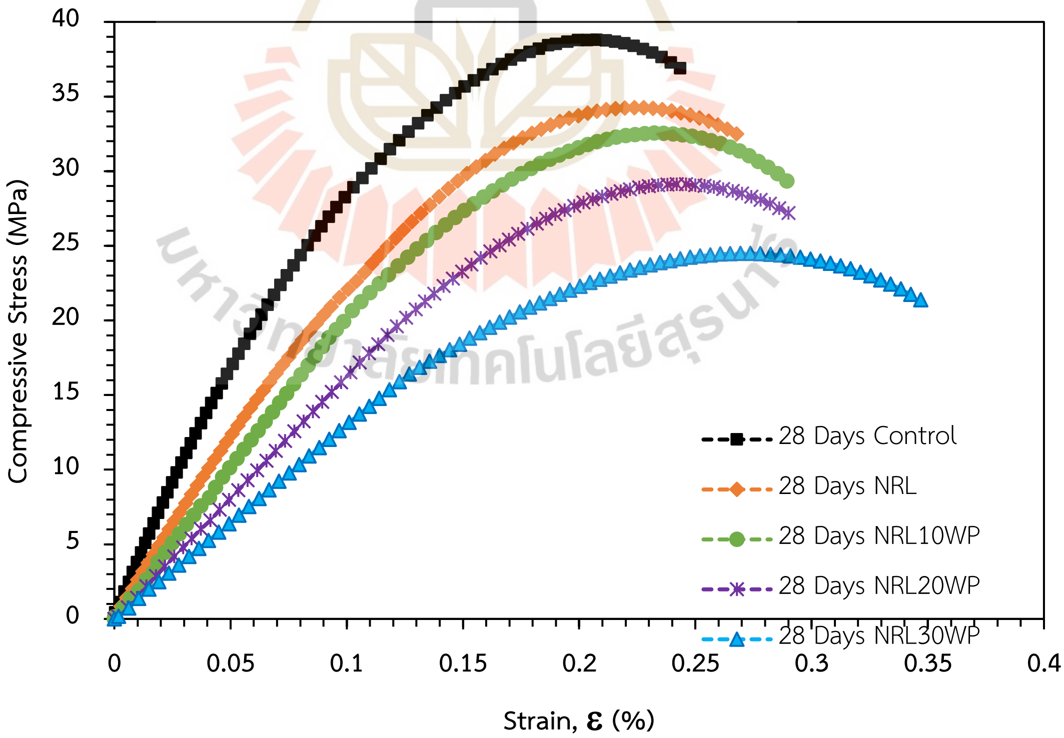


Figure 4.10 Stress-stain curve at 28-days of waste polymer concrete using NRL.

4.3 Flexural Strength

The prismatic HFRC specimens, measuring 75×75×300 mm, were divided into three sections for the third-point flexural load test to obtain the modulus of rupture (MOR) or flexural strength (ff). The development of flexural strength in HFRC from 7 days to 28 days ranged between 55% to 65% of the strength at 7 days, as shown in Figure 4.11. The control sample, NCA-0.0H-FRC, using NCA, had a flexural strength value of 5.53 MPa. Surprisingly, the addition of 0.5% hemp fiber reinforcement by volume weight increased the flexural strength by 7.2% for NCA-0.5H-FRC. In contrast, incorporating 0.75% hemp fiber in NCA-0.75H-FRC resulted in a 3.8% reduction in strength, and further adding 1.0% hemp fiber in NCA-1.0H-FRC led to a 5.0% reduction, amounting to a total reduction of 9.2%. Similarly, RCA-0.0H-FRC achieved a flexural strength of 4.60 MPa, representing a 16.8% difference compared to NCA-0.0H-FRC. Additionally, RCA-0.5H-FRC notably increased flexural strength by 6.96%, while RCA-0.75H-FRC experienced a modest drop of 1.09%, and RCA-1.0H-FRC exhibited a significant decrease of 6.3% when reinforced with 1.0% hemp fiber. Figures 4.12 and 4.13 illustrate the relationship between flexural strength and deformation of HFRC for both RCA and NCA, demonstrating the behavior of HFRC in two different scenarios. Without hemp fiber, the concrete was weak in terms of deformation, unable to absorb more energy after reaching its maximum strength, and ultimately failing as a brittle material. In the second scenario, when reinforced with hemp fiber in an appropriate amount, the HFRC showed the ability to sustain force after reaching the peak strength, thanks to the high elasticity of the hemp fiber in the concrete matrix. According to DH-S 309/2544, the minimum requirement for flexural strength in pavement is 4.2 MPa. In this regard, HFRC using NCA and RCA samples passed the requirement for all samples. Notably, reinforcing with 0.5% hemp fiber yielded positive results in terms of both flexural strength and a slight reduction in compaction, which will be further investigated in the next study on fatigue flexural strength to examine the response behavior for mechanistic-empirical design. Figures 4.14 and 4.15 below show flexural failure of hemp fiber reinforced concrete using NCA and RCA. Without fiber, concrete samples broke at the middle and divided into 2 portions which illustrated that no tensile strength for normal concrete, whereas, reinforced with hemp fiber, HFRC changed the behavior of broken to cracking in accordance with assistance of hemp fiber which provided tensile strength and bond the concrete together under the vertical applied load. Therefore, hemp fiber provided higher energy absorption than concrete.

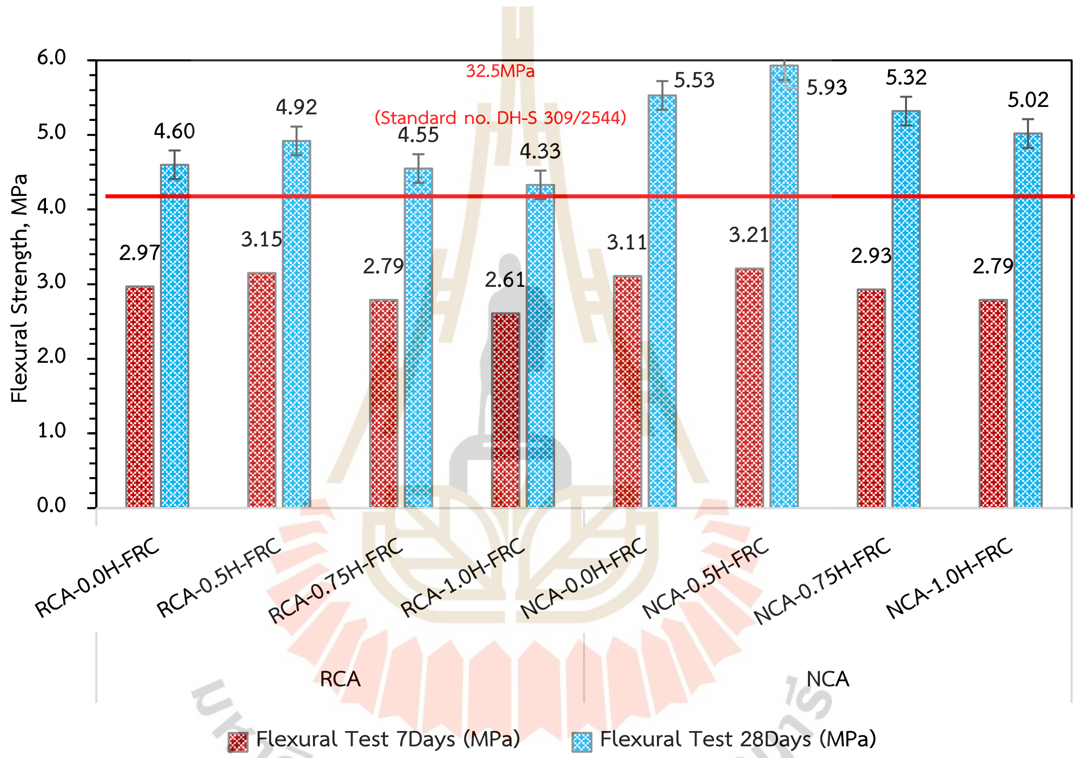


Figure 4.11 Strength development of flexural strength using NCA and RCA.

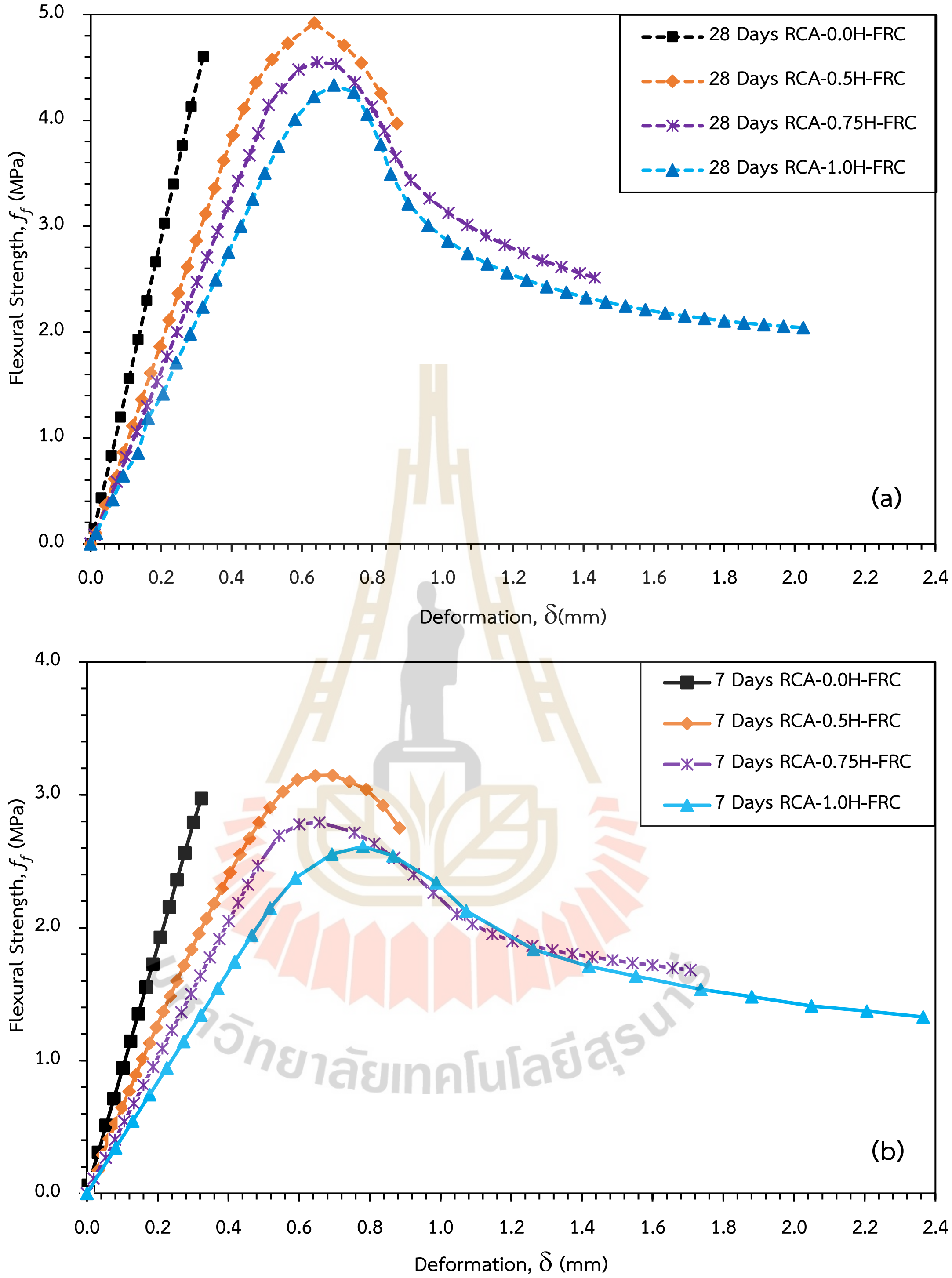


Figure 4.12 Flexural Stress-deformation curve of (a) 28-days and (b) 7-days using RCA.

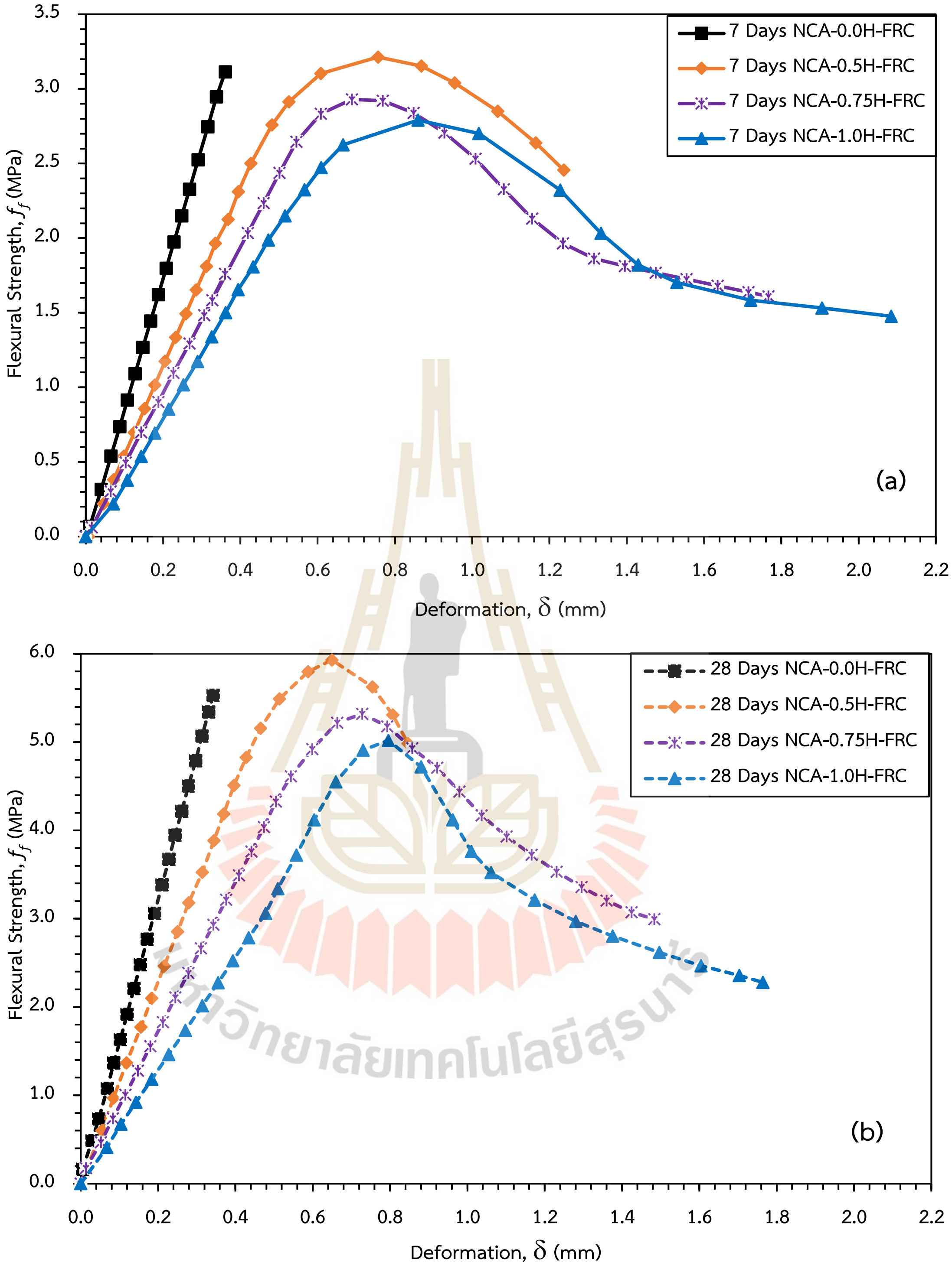


Figure 4.13 Flexural Stress-deformation curve of (a) 28-days and (b) 7-days using NCA.

Figure 4.14 Flexural failure of hemp fiber reinforced concrete using NCA.

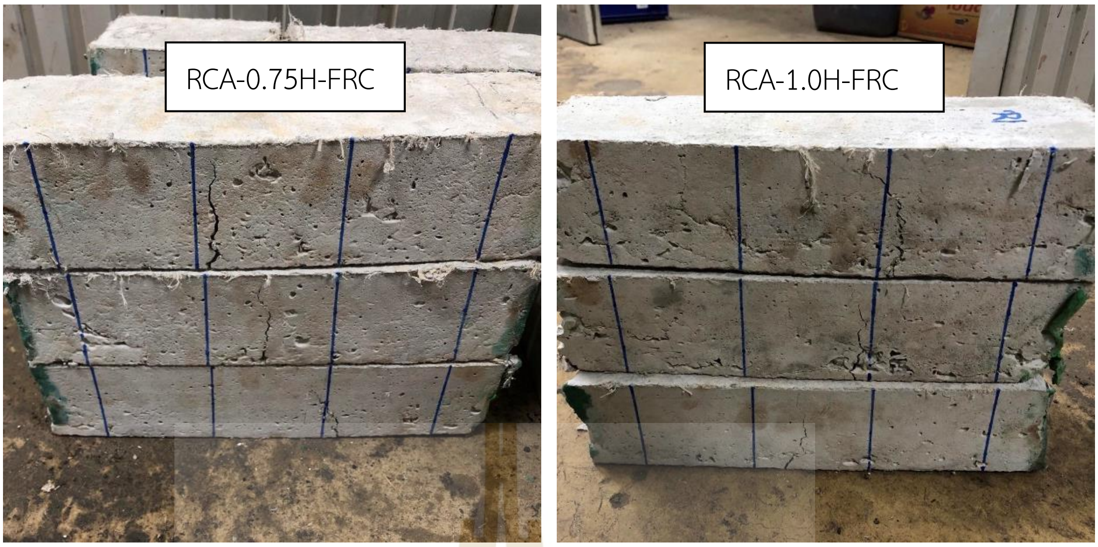


Figure 4.15 Flexural failure of hemp fiber reinforced concrete using RCA.

The flexural strengths of normal concrete, NRL-modified concrete, and NRL-modified waste polymer concrete samples cured at 7, 14, and 28 days are shown in Figure 4.16. The solid line represents the minimum 28-day flexural strength requirement ($f_f \geq 4.2$ MPa) for concrete pavement specified by DOH, Thailand (DoH, 1996). For normal concrete, the flexural strength increased with curing time as expected; flexural strength initially was 2.8 MPa, 4.3 MPa, and 4,7 MPa at 7, 14, and 28 days, respectively, which met the specification. Figure 166 shows that the NRL additive can increase the flexural strength of concrete that has been modified with NRL, and its flexural strength was about 3.3% higher than that of normal concrete curing at 28 days. The flexural strength of NRL-modified concrete was 2.9, 4.3, and 4.86 MPa at 7, 14, and 28 days, respectively. This is because the NRL modifies the microstructure of the concrete, making it denser and reducing the gaps between particles, which prevents water alteration in the matrix and modifies the chemical reaction phases (Yaowarat et al., 2021; Suddeepong et al., 2022). When compared to normal concrete, it was discovered that the replacement of the aggregate with PET and crumb rubber reduced the flexural strength. The flexural strength of concrete with PET and crumb rubber aggregate replacement decreased with increasing the replacement ratios. Although the flexural strength was reduced, the 28-day flexural strength of NRL10WP was 4.4 MPa, which met the minimum requirement of 4.2 MPa. Furthermore, at the age of 28 days, NRL10WP, NRL20WP, and NRL30WP concrete were respectively 5.2%, 24.9%, and 36.9% flexural strength lower than the normal concrete. The percentage reduction in flexural strength of NRL10WP was lower than the similar studies using PET or crumb rubber aggregate in concrete as a rigid pavement from the previous research (Youssf et al., 2016). This implies that in NRL-modified concrete with PET and crumb rubber aggregate replacement, NRL additive can enhance the development of flexural strength.

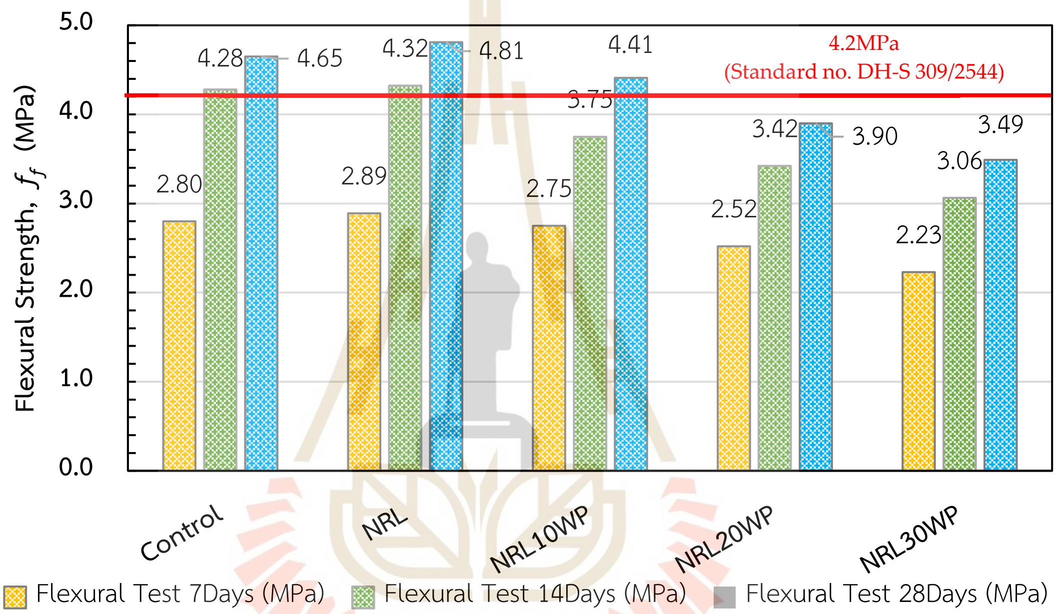


Figure 4.16 Strength development of flexural strength of waste polymer concrete using NRL.

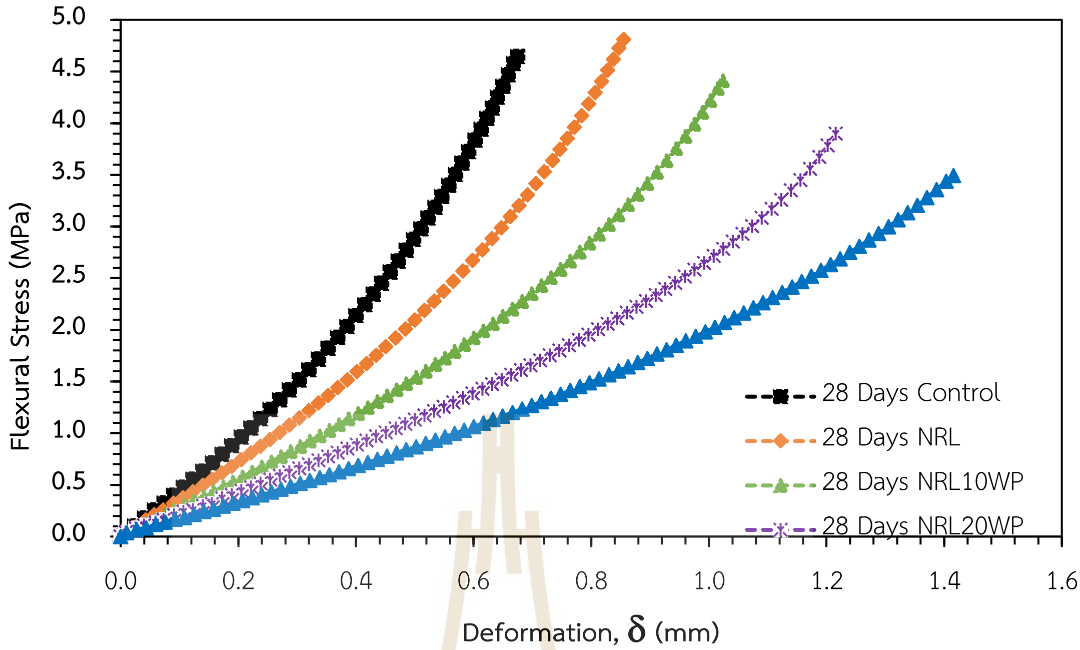


Figure 4.17 Flexural Stress-deformation curve at 28-days of waste polymer concrete using NRL.

4.4 Mechanical Properties of HFRC and Waste Polymer Concrete

Table 4.1 summarized the mechanical properties of HFRC which had modulus of elasticity, and modulus of toughness for compressive and flexural. Modulus of elasticity was obtained from the stress-strain curve of figure 4.5 and 4.6. Starting with control sample of NCA-0.0H-FRC which produced the maximum elastic modulus of 25.20 GPa. Reinforced with 0.5%, 0.75%, and 1.0% of hemp fiber resulted in reduction modulus of elasticity by 20.6%, 25.0%, and 42.9%, respectively. RCA-0.0H-FRC provided similar behavior of using NCA but a minor reduction in modulus of elasticity which began with 19.60 GPa and continuously adding fiber of 0.5%, 0.75%, and 1.0% decreased 5.1%, 21.4%, and 34.7%, correspondingly.

The compressive toughness modulus was determined to indicate the energy absorption of the concrete under the applied force from figure 4.5 and 4.6 which relatively with compressive strength. For RCA aggregate, the energy absorption under elastic curve was began with 4.85 MJ/m^3, additional of 0.5% hemp fiber increased to 5.20 MJ/m^3 counted as 7.20%. In contrast reinforced with 0.75% and 1.00% decreased

14.2% and 17.1%, compared to the control sample. Natural coarse aggregate control sample produced 4.46 MJ/m^3, an addition of 0.5% hemp fiber improved area of absorption to 4.86 MJ/m^3 counted as 8.5%. Moreover, reducing 0.2% and 13.0% for 0.75% and1.0% of hemp fiber reinforcement in concrete samples.

Flexural toughness indicated the area of energy absorption of the sample under flexural stress from figure 4.10 AND 4.11, starting with the NCA-0.0H-FRC had 0.95 MJ/m^3 and increased significantly to 2.27 MJ/m^3, 2.20 MJ/m^3, and 2.08 MJ/m^3 when reinforced hemp fiber 0.5%, 0.75%, and 1.0%, respectively. Likewise, flexural toughness of RCA-0.0H-FRC was 0.74 MJ/m^3 and grew to 1.82 MJ/m^3, 1.65 MJ/m^3, and 1.64 MJ/m^3 in addition of hemp fiber 0.5%, 0.75%, and 1.0%. Flexural toughness was clearly shown that the energy absorption after reinforcement was much higher than normal concrete which provided the maximum of 0.5% volume of hemp fiber for both using RCA and NCA.

The density of normal concrete is in the range of 2300 to 2450 $kg.m^{-3}$ which NCA sample had 2411.9 $kg.m^{-3}$. Relatively to low density of hemp fiber made the concrete had lower density by adding more fiber. For NCA, 0.5%, 0.75%, and 1.0% were reduced respectively to 2346.7 $kg.m^{-3}$, 2311.1 $kg.m^{-3}$, and 2275.6 $kg.m^{-3}$. RCA had lower density compared to NCA which resulted in lower density which began with control sample had the density of 2352.6 $kg.m^{-3}$, a minor reduction of density was occurred by the higher percentage represented in concrete which were 2881.5, 2257.8, 2240.0 for 0.5%, 0.75%, and 1.0%, respectively.

Table 4.1 demonstrates the mechanical properties, including density, modulus of elasticity, compressive and flexural toughness, or modulus of resilience of the studied concrete samples. As per the mix design, the density of the control concrete sample was 2386.4 kg/m3, which is within the range of normal concrete's typical densities of 2350 and 2400 kg/m3. The NRL-modified concrete had a density of 2385.2 kg/m3, which indicated that the NRL additive had less effect on the density. Identically, the PET and crumb rubber aggregate replacement resulted in reducing the density of the concrete samples. The NRL10WP, NRL20WP, and NRL30WP had densities of 2342.3, 2325.6, and 2305.4 kg/m^3, respectively, in which they were reduced about 1.9%, 2.6% and 3.4% compared to normal concrete. Figure 4's compressive stress-strain curve at 28 days was used to determine modulus of elasticity (Young's modulus) values for the samples under analysis. The results are re-ported in Table 5. The normal concrete's modulus of elasticity typically ranges between 30 and 50 GPa, while the current control concrete sample's modulus of elasticity was 33.91 GPa. In comparison with the control sample, the concrete modified with NRL had an elasticity modulus that was about 28.4% lower. In contrast, as replacement ratios were increased in NRL-modified concretes with PET and crumb rubber aggregate replacement, the modulus of elasticity noticeably reduced. NRL10WP, NRL20WP, and NRL30WP had elasticity moduli of 20.4, 16.2, and 13.04 GPa, respectively.

The compressive toughness was used to demonstrate the energy absorption under the compressive mode. The compressive toughness (measured in MJ/m^3) of the studied samples can be determined from their compressive stress-strain curve depicted in Figure 4.10. The control sample had a compressive toughness of 5.35 MJ/m3 while the NRL-modified had compressive toughness 4.89 MJ/m^3 or was about 8.6% lower than the normal concrete. The compressive toughness of NRL10WP, NRL20WP, and NRL30WP was 4.74, 4.30, and 4.22 MJ/m^3, respectively. In other words, the compressive toughness of the NRL-modified concrete was reduced by about 11.4%, 19.6%, and 21.1% with 10%, 20%, and 30% of PET and crumb rubber aggregate replacement, respectively, when compared with the control sample.

On the other hand, the flexural toughness characteristics of NRL-modified concrete with and without PET and crumb rubber replacement were found to be different from their compressive toughness. The flexural toughness is used to indicate the energy absorption of the studied concrete when subjected to bending stress, such as the traffic loading on the concrete slab. The bending stress generated by repeated traffic loading can cause distress in the rigid pavement, which is considered the major mode of failure of concrete pavement. Therefore, the concrete’s ability to absorb energy (fracture energy), or known as flexural toughness, can positively impact the service life of a rigid pavement. This characteristic allows the pavement to resist crack propagation better, which is particularly important considering the dynamic loads and environmental impacts pavements are subjected to (Lohaus et al., 2007). When the concrete has a higher energy absorption capacity, it means it can deform more before fracturing. This deformation distributes stresses over a large volume of the material, which can prevent or delay the initiation of cracks. Furthermore, even when cracks do start, the higher energy absorption capacity can help prevent the rapid growth of these cracks (Wille et al., 2014). As such, it increases the pavement's durability and resilience against various forms of distress, potentially extending its service life.

The flexural toughness values of the studied concrete samples shown in Table 4.1 were determined in MPa.m and obtained from their flexural stress-strain curves, as shown in Figure 4.17. It clearly indicated that the energy absorption of the NRL-modified concrete (1.65 MPa.m) was higher than that of normal concrete (1.29 MPa.m). This confirms that the introduction of NRL additive can improve the flexural strength and energy absorption capabilities of normal concrete. It is quite interesting to observe that even though the flexural strength values of the NRL-modified concrete with PET and crumb rubber aggregate re-placement were lower than the normal concrete, the values of their flexural toughness were greater than those of normal concrete. The NRL-modified concrete with waste aggregate replacement also had a higher energy absorption capacity as replacement ratios were raised. It implies that the NRL-modified concrete with PET and crumb rubber aggregate replacement had better ductility behavior than that of the normal concrete.

Table 4.1 Mechanical properties of HFRC and waste polymer concrete using NRL.

Sample	*Density Of HFRC* $kg.m^{-3}$	*Modulus of Elasticity GPa*	*Flexural Toughness MPa*	*Compressive Toughness* MJ/m^3
NCA-0.0H-FRC	2411.9	25.2	0.95	4.46
NCA-0.5H-FRC	2346.7	20.0	2.27	4.84
NCA-0.75H-FRC	2311.1	18.9	2.20	4.45

NCA-1.0H-FRC	2275.6	14.4	2.08	3.88
RCA-0.0H-FRC	2352.6	19.6	0.74	4.85
RCA-0.5H-FRC	2281.5	18.6	1.82	5.20
RCA-0.75H-FRC	2257.8	15.4	1.65	4.16
RCA-1.0H-FRC	2240.0	12.8	1.64	4.02
Control	2386.4	33.9	1.29	5.533
NRL	2385.2	24.27	1.65	4.48
NRL10WP	2342.3	20.37	1.81	4.74
NRL20WP	2325.6	16.8	1.89	4.30
NRL30WP	2305.4	13.04	2.02	4.22

4.5 SEM Analysis of HFRC

Figures 4.18 and 4.19 showed 6 different images of sample of HFRC using recycled concrete aggregate and natural coarse aggregate reinforced with 0 % (a), 0.5 % (b), and 1.0 % (c) of hemp fiber reinforcement with similar behavior. Without hemp fiber reinforcement was generally homogenous due to the particle distribution of aggregate and cement mortar which produced rigid bonding. HFRC of 0.5 % displayed a better cement mortar attached to the surface of hemp fiber according to its low content of hemp fiber which ensured higher CSH to secure the bonding in concrete matrix compared to large amounts of reinforcement 1.0 % which clearly had less adhesion to concrete elements. Thus, the trend of adding more hemp fiber to the concrete matrix will significantly reduce the adherence for both flexural and compressive strength but HFRC with 0.5 % provided a proper amount of hemp fiber which was great at connecting the concrete particles and resulted in better for flexural strength that had a failure mode of fiber rupture. The consistency of HFRC was most likely to depended on homogeneity of hemp fiber, where treated hemp fiber provided a better bonding for concrete matrix which basically showed in figure 4.16b that after treatment with 6% of NaOH solution increased the surface roughness and adhesion to hemp fiber which helped on resisting pull-out force in concrete matrix. Figure 4.20a investigated the surface of untreated hemp fiber which had a smooth surface and attached with dusty, and it proved that treating the fiber could clean the impurity.

Morphological studies were conducted to comprehend the microstructure of waste polymer concrete. To describe the microstructural evolution of the investigated concrete mixes, a scanning electron microscopy (SEM) inspection using selenium detectors and a 5 kV SEM was used. Figure 4.21 displays the SEM images of the 28-day-cured NRL10WP, NRL30WP, normal concrete, NRL-modified concrete, and normal concrete at magnifications of 1,000 and 5,000, respectively. Figure 21a shows that the typical concrete mix (without NRL and waste materials) had large amounts of calcium silicate hydrate (C-S-H) gel, $Ca(OH)_2$, and ettringite. This confirmed that the strength of the concrete was theoretically developed in accordance with the production of hydration products.

Figure 21b shows the SEM images of NRL-modified concrete, which demonstrated that its matrix became significantly less rigid than typical concrete. This might be due to the effect of NRL additive generated film network blocking the growth of hydration products, resulting in lower compressive strength. However, the film network was detected to cover and bridging the C-S-H gels and aggregates. Furthermore, less ettringite was detected and resulted in enhanced adhesion or bonding between the aggregates by film network. Therefore, the concrete modified with NRL developed flexural strength (Yaowarat et al., 2021; Suddeepong et al., 2022). In addition, the NRL film network can absorb energy and helps to mitigate crack propagation in the concrete, which reduces the likelihood of a brittle failure. This confirmed the improvement of concrete's toughness and ductility as demonstrated in Figure 5.

Figure 21c illustrates the SEM images of NRL-modified concrete with 10% of PET and crumb rubber aggregate replacement (NRL10WP). It clearly indicated the connection between the waste aggregates and hydration products, resulting in several pores and a loose matrix. This led to the reduction of its compressive and flexural strength. SEM images of NRL-modified concrete with 30% of PET and crumb rubber aggregate replacement (NRL30WP) was demonstrated in Figure 8d. It was evident that the higher rate of PET and crumb rubber aggregate replacement affects the microstructure by creating a weaker interface between the aggregate and the cement paste. PET and crumb rubber are hydrophobic and non-polar materials, which make it difficult for the cement paste to bond with the PET and crumb rubber particles. Subsequently, this can lead to a remarkably decrease in com-pressive strength. However, the inclusion of PET and crumb rubber can increase the concrete's ability to absorb energy, improving its toughness and resistance to impact and dynamic loads due to its plastic deformation characteristics (Atahan et al., 2012).

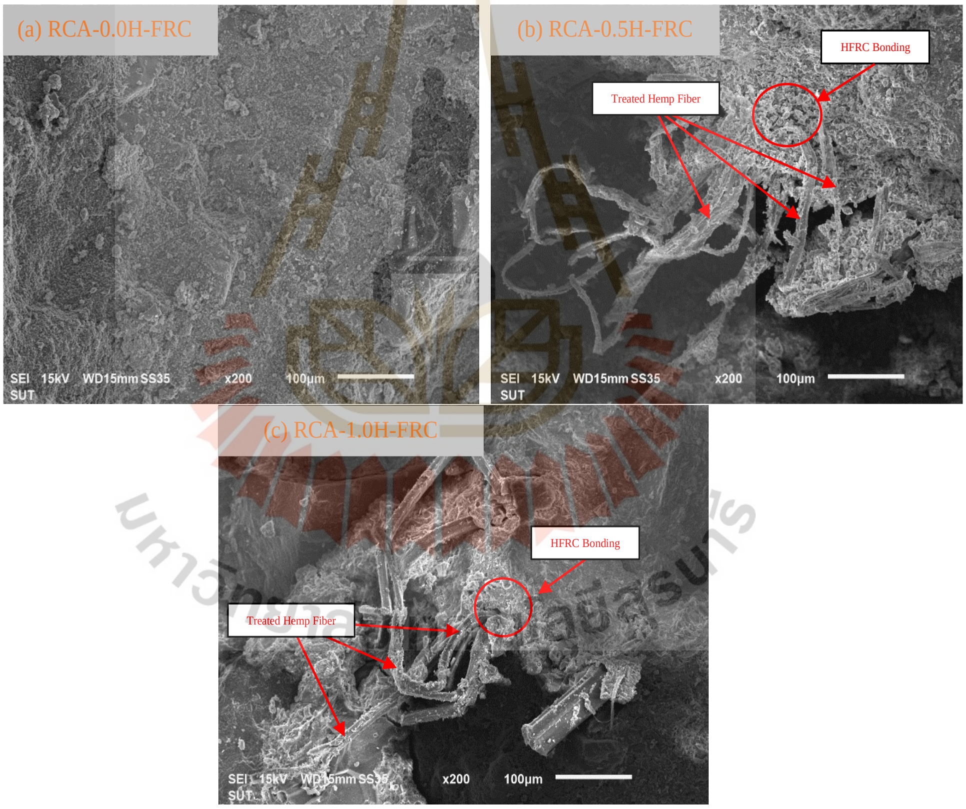


Figure 4.18 SEM of RCA-0.0H-FRC, RCA-0.5H-FRC, and RCA-1.0H-FRC.

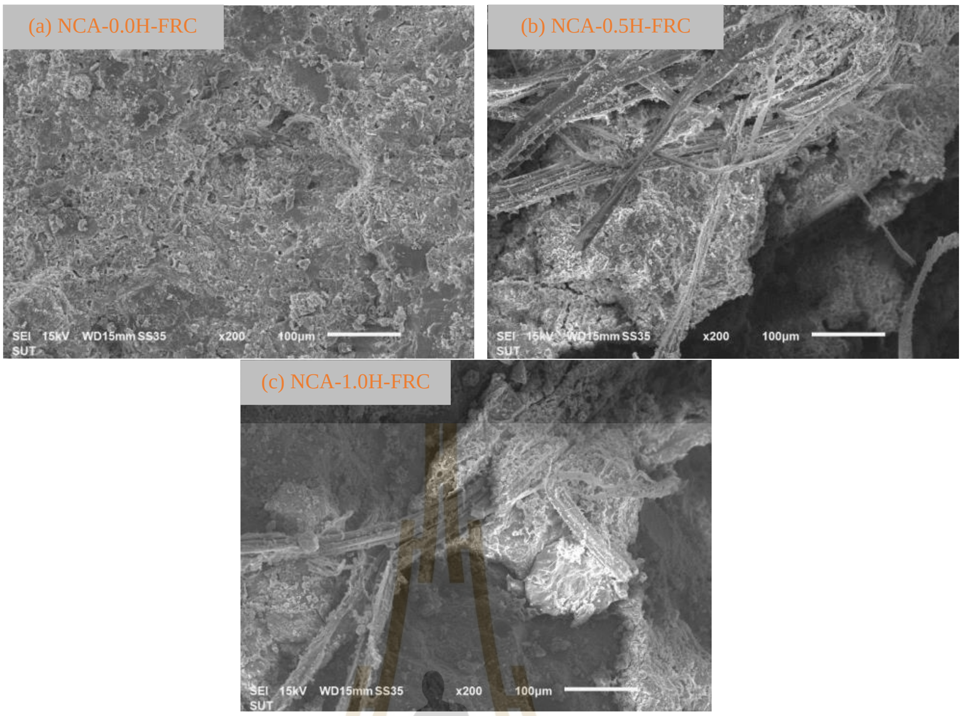


Figure 4.19 SEM of NCA-0.0H-FRC, NCA-0.5H-FRC, and NCA-1.0H-FRC.

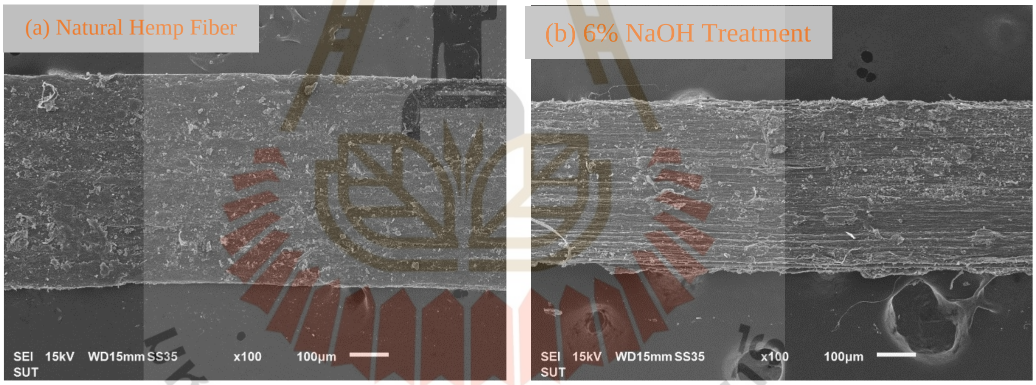


Figure 4.20 SEM of natural hemp fiber and treatment hemp fiber with NaOH.

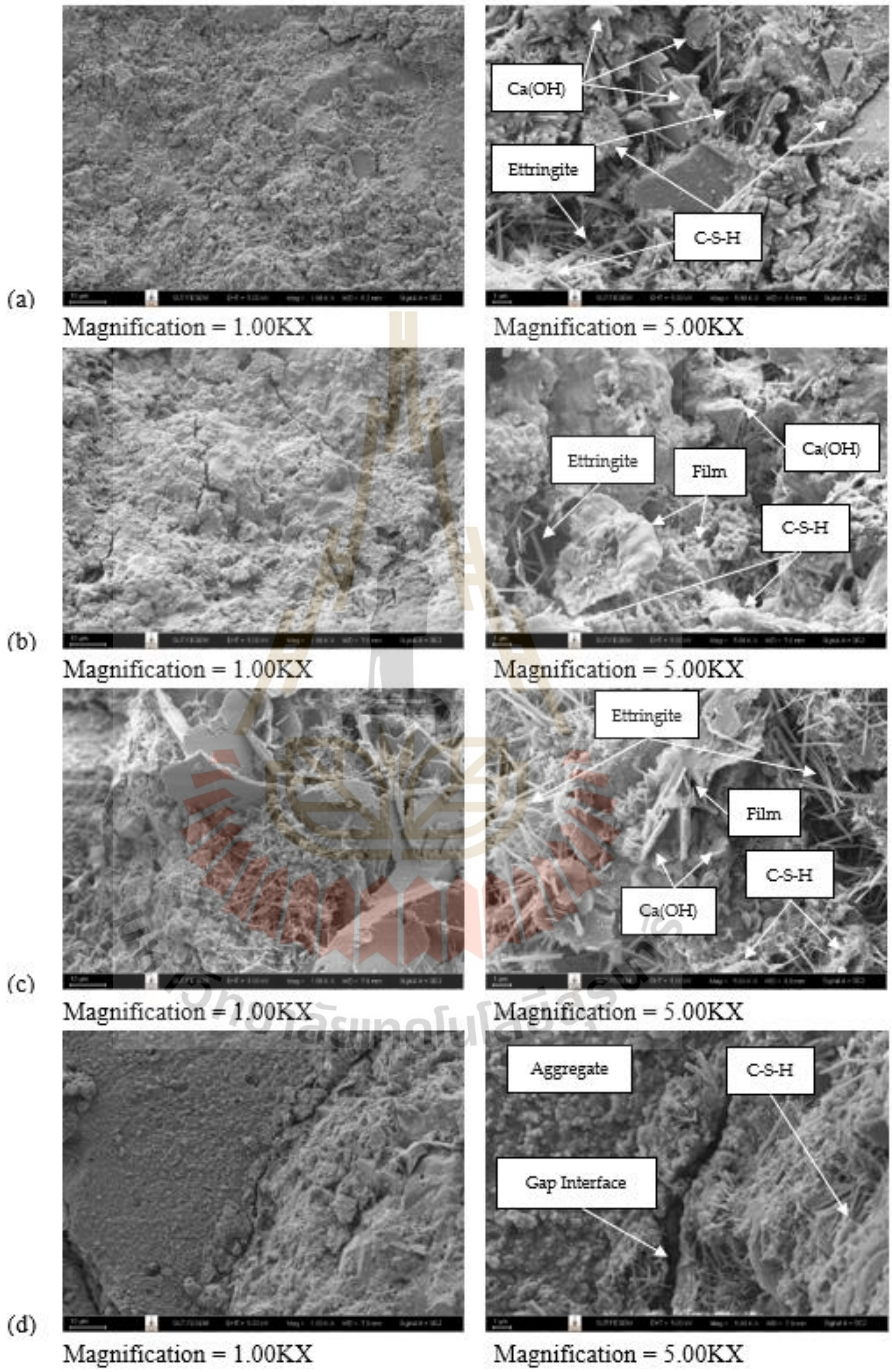


Figure 4.21 SEM image of: (a) Normal Concrete, (b) NRL-modified concrete, (c) NRL10WP, and (d) NRL30WP.

4.6 Flexural Fatigue of HFRC

The diagram in figure 4.22 illustrates the way in which concrete behaves under fatigue loading. The fatigue response of concrete can be broken down into three main mechanisms. The first mechanism occurs in the initial zone where the repetitive loading breaks down the bonds that hold the concrete structure together, creating weak areas with broken bonds. Cracks begin to form in the weak areas and propagate into zone 2. In zone 3, the cracks rapidly propagate and eventually lead to fatigue cracking failure at the transition between zones 2 and 3 (Lee and Barr 2004). The fatigue life of the sample, denoted as N_f, is measured by the number of repetitive loadings required to destroy it.

Figures 4.23, 4.24, and 4.25 showed 3 different fatigue responses in deformation and number of cycles caused by 60%, 70%, and 80% stress ratio, respectively. Control samples of RCA and NCA which are RCA-0.0H-FRC and NCA-0.0H-FRC applied stress of 80% at 3.68 MPa and 4.42 MPa had almost similar response of 180 and 177 cycles compared to PCA 1984 of 119 cycles which was in acceptable range. Additional of 0.5% of hemp fiber, RCA-0.5H-FRC and NCA-0.5H-FRC increased the cycles by 75% and 158%. In the same trend, reinforcing 0.75 % of hemp fiber raised 129% and 208% compared to non-reinforcement for RCA and NCA. Unfortunately, for 1.0% of FHRC had a small increase in 9% and 43% compared to normal concrete but a large decrease compared to 0.5% and 0.75% of HFRC of RCA and NCA. A stress ratio of 70% of 3.22 MPa and 3.87 MPa was applied to concrete samples of RCA and NCA that provided 1902 and 2600 cycles which satisfied with PCA 1984 that had 1922 cycles. Furthermore, RCA-0.5H-FRC and NCA-0.5H-FRC of SR 70% which were 3.44 MPa and 4.42 MPa provided 403% and 338% increasing of cycles. Surprisingly, adding 0.75% the cycles with applied stress of 3.29 MPa and 3.72 MPa were increased to 1131% and 884% compared to control samples RCA and NCA. Moreover, HFRC of 1% had the highest improvement up to 1465% for RCA and 1009% for NCA with the applied stress of 3.03 MPa and 3.51 MPa. Along with a 60% stress ratio, 2.76 MPa and 3.01 MPa were applied to concrete beams using RCA and NCA that responded with 38483 cycles and 28017 cycles which still in bearable of PCA curve in 1984. For RCA, reinforcing with 0.5, 0.75 and 1% of hemp fiber increased 77, 92 and 103%, whereas, NCA had similar number of cycles grew 95, 161 and 188% compared to plain concrete, respectively.

Reinforcing hemp fiber in the concrete provided a better in repeated loads for these 3 stress ratios which meant the tensile strength of hemp fiber had the ability to absorb more tensile energy. Despite the repetition number of cycle, the deformation of 80% stress ratio was failed mostly at 0.5 mm, 70% of SR had an extension of deformation to 0.8mm and 60% had the most enlargement to 1.0 mm. Therefore, the smaller applied load to the concrete element assisted in fiber yielding to prevent the cracking behavior. Due to the figure 4.18, 4.19, and 4.20, the higher reinforcement of hemp fiber serviced the higher repeated loads, unfortunately according to the figure 4.4 illustrated the requirement of compressive strength from DOH-S309-2544 is 32.5 MPa which reinforcement with 0.75% and 1.0% did not pass the primary condition of both RCA and NCA but were acceptable for flexural strength requirement of the equal or higher than 4.2 MPa in figure 4.7. Therefore, the optimum reinforcement of HFRC is 0.5% by the volume weight of concrete that can be used for the data analysis and design in relationship between stress ratio and fatigue life compared to the PCA curve in 1984.

Figure 4.26 showed the average linear relationship in logarithm between fatigue life and applied stress ratio of the concrete samples. Since HFRC using RCA and NCA had similar behaviors responded to cyclic loads, therefore, the average linear progression can be applied and used for both materials. In mechanistic-empirical method of rigid pavement from PCA 1984, the design of concrete pavement is based on the applied load and convert into allowable repetitions to obtain the fatigue damage of the design lanes which PCA has been used worldwide in the past. Positively, additional hemp fiber in the concrete can extend the fatigue life of the concrete due to high tensile strength of the fiber for both RCA and NCA on the volume of 0.5% and 0.75%. The 5% extension upper boundary of PCA curve was lower than 0.5% and 0.75% which indicated that reinforced with hemp fiber is claiming the advantages to use in pavement applications. Based on the linear regression analyses of the relationship between stress ratio and fatigue life, the equation of any stress ratios applied to the samples can be determined the fatigue life by using the following equations below:

PCA 1984 : $\text{Log}\ (N_f) = 11.810 - 12.165(SR)$ (3)

0.5H-FRC : $\text{Log}\ (N_f) = 12.247 - 12.061(SR)$ (4)

0.75H-FRC : $\text{Log}\ (N_f) = 12.629 - 12.405(SR)$ (5)

1.0H-FRC : $\text{Log}\ (N_f) = 14.367 - 14.973(SR)$ (6)

Where N_f = maximum number of repetitions and SR = stress ratio.

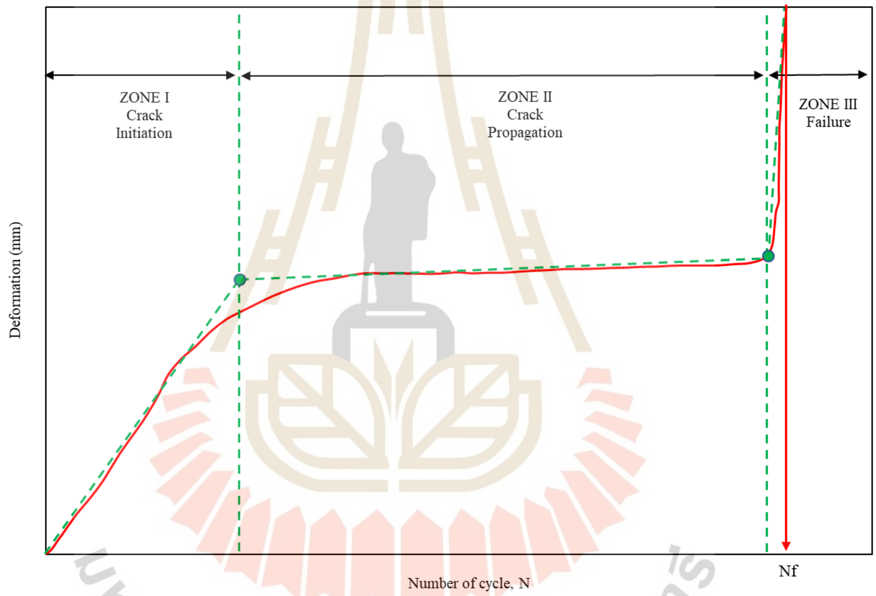


Figure 4.22 Relationship between deformation and N_f under applied flexural stress.

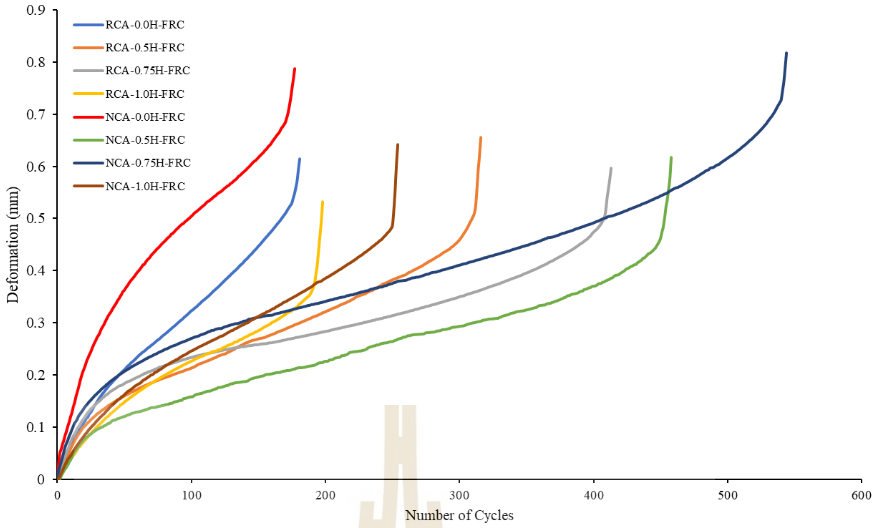


Figure 4.23 Deformation and N_f of NCA and RCA at 80% applied stress ratio.

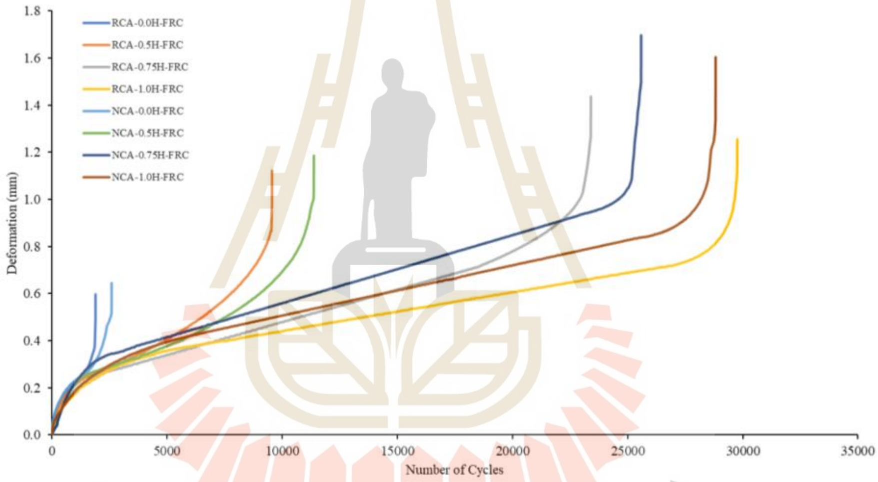


Figure 4.24 Deformation and N_f of NCA and RCA at 70% applied stress ratio.

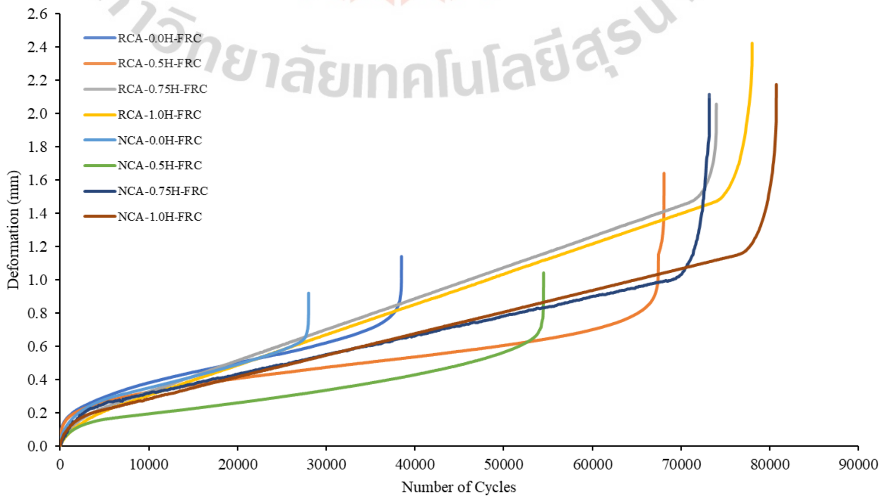


Figure 4.25 Deformation and N_f of NCA and RCA at 60% applied stress ratio.

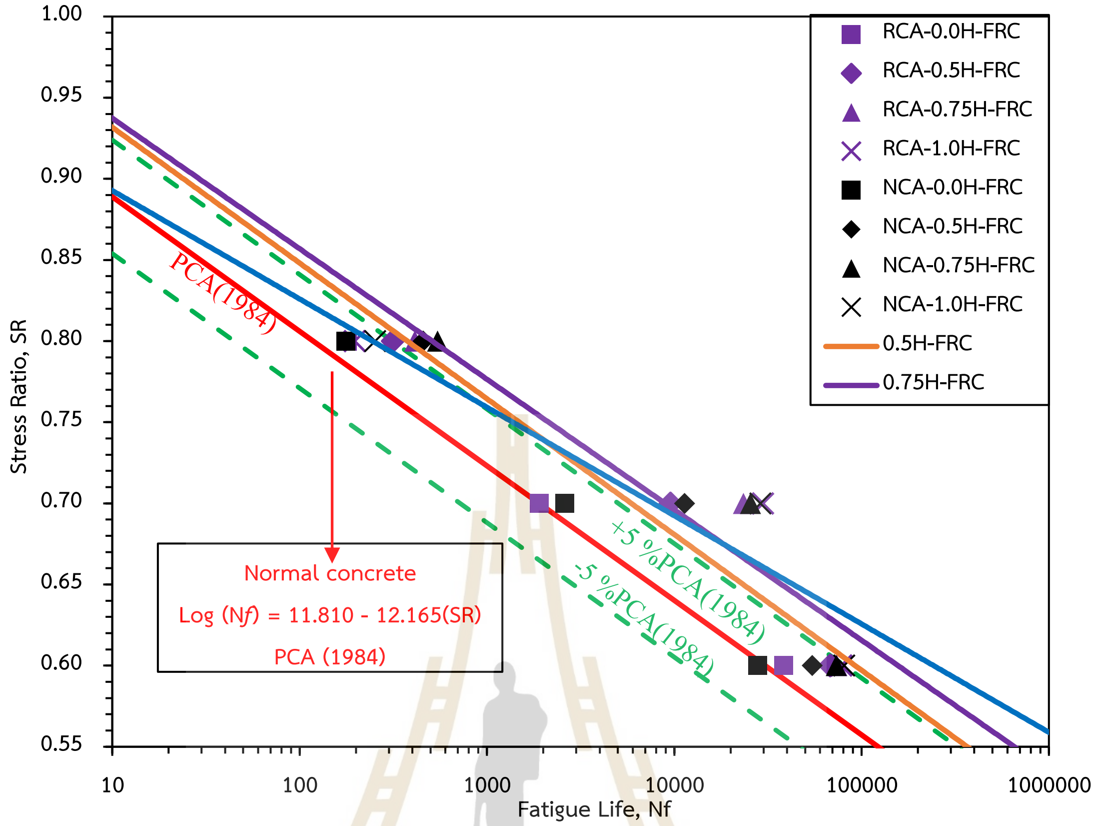


Figure 4.26 Relationship between fatigue life and stress ratio of various HFRCs.

CHAPTER V
CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusion

This research study evaluated the importance of using hemp fiber for improving the mechanical strength of concrete, which also examined for both aggregate natural coarse aggregate (NCA) and recycled concrete aggregate (RCA). Also, replacing concrete aggregates by using waste polymer such as PET and crumb rubber blended with natural rubber latex to utilize as an alternative method to drive concrete industries to be environmentally friendly. The mechanical properties of hemp fiber reinforced concrete (HFRC) and waste polymer concrete were tested to follow the requirement of Department of Highway, Thailand to be used in as a sustainable pavement material. Both NCA and RCA had different behaviors during adding various hemp fiber percentage in 0.0% (control sample), 0.5%, 0.75%, and 1.0% with a constant water to cement ratio of 0.5. Whereas waste polymer concrete replaced the aggregate of PET and crumb rubber in 10, 20, and 30% mixing with natural rubber latex. To be considered as pavement material, two parameters such as compressive and flexural strength was a must to meet minimum requirement, thereafter, number of repetitions of HRFC samples to be lastly tested in flexural fatigue test in between stress ratio of 60%, 70%, and 80% of flexural strength to observe concrete behavior. The following significant findings was found and summarized from this study below:

I. For all samples, NCA produces a better quality compared to RCA in compressive strength, flexural strength, density, modulus of elasticity, compressive toughness, flexural toughness but fatigue test provides similar number of repetitions.

II. For control samples using NCA provides higher value of compressive, and strength compared to RCA, but RCA reduced a small amount of strength compared to NCA which showed the importance of controlling materials in grading of all aggregate. For both RCA and NCA material with addition higher percentage results in reduction in compressive strength but improves to obtain higher compressive strain which valuable in compressive toughness.

III. A proper amount of hemp fiber addition in concrete produces higher flexural strength with higher deformation of concrete, for example reinforced with 0.5% of volume for NCA and RCA. To obtain a higher deformation more percentage of hemp fiber should be presented but trade-off with reduction in flexural strength, for example reinforced with 0.75% and 1.00% of volume for NCA and RCA.

IV. Compressive toughness is examined in area under maximum resistance and illustrates that putting 0.5% of hemp fiber gives a higher energy absorption to samples while adding 0.75%, and 1.00% reduces compressive toughness compared to control samples for both RCA and NCA. Even the compressive strain increases but compressive strength largely reduces and brings this into lower toughness.

V. Flexural toughness is produced in the area between the flexural strength and deformation. A higher deformation and flexural strength for 0.5% hemp fiber sample turns out to be maximum for NCA and RCA. Whereas control sample produces minimum toughness due to the low flexibility causes to rapidly fail the sample. 0.75% and 1.00% assists flexural toughness to higher than control because of large yielding in deformation.

VI. According to higher energy absorption, HFRCs provides less cracking to samples in compressive and flexural which will solve cracking problem for traditional rigid pavement.

VII. Density of HFRC samples decrease in higher percentage adding of hemp fiber which are caused by lower specific gravity of hemp fiber involvement. In the same trending, modulus of elasticity decreases simultaneously according to reduction of compressive strength on stress-strain curve.

VIII. With the addition of NRL additive, the compressive strength of the NRL-modified concrete was lower than the normal concrete. At the age of 28 days, the compressive strength of NRL10WP, NRL20WP, and NRL30WP was about 8.3%, 15%, and 28.5% lower than that NRL-modified concrete. However, the 28-day compressive strength of NRL-modified concrete and NRL10WP was 34.25 MPa and 32.54 MPa and met the minimum compressive requirement (fc ≥ 32 MPa) for concrete pavement specified by DOH, Thailand.

IX. The flexural strength of NRL-modified concrete was approximately 3.3% higher than normal concrete. Similar to the compressive strength behavior, the flexural strength of NRL-modified concrete with PET and crumb rubber aggregate replacement decreased with increasing replacement ratios. However, the flexural strength of NRL10WP was found to meet the minimum flexural strength requirement ($f_f \geq 4.2$ MPa), for rigid pavement specified by DOH, Thailand. In terms of mechanical strength properties, it is confirmed that 10% of waste PET and crumb rubber aggregate replacement can be used in concrete mix for rigid pavement design.

X. Microstructural analysis indicated that the addition of NRL additive generated the film network to prevent the development of hydration products and resulted in com-pressive strength reduction. However, this film network acts as a bridge mechanism to enhance the adhesion or bonding between the aggregates in the concrete matrix, leading to improved flexural strength. PET and crumb rubber are hydrophobic and non-polar materials, hence increasing the amount of these materials in the concrete mix can affect their microstructure by creating weaker interfaces between aggregates and cement pasted. As such, the mechanical strength dropped. However, the NRL-modified concrete with PET and crumb rubber aggregate replacement can help the concrete's ability to absorb energy and improving its toughness and resistance to impact and dynamic loads.

XI. Optimum reinforcement percentage of hemp fiber is at 0.5% which exhibits a higher number of repetitions compared to control sample. Moreover, the relationship between deformation and number of cycles showed that less stress ratio delivers higher deformation which related to resistance of hemp fiber in concrete materials. Number of repetitions is the most important in pavement design parameter to decide for thickness of the pavement that can influence cost of pavement construction which HFRCs provided more than 5% better compared to traditional PCA 1984 curve.

XII. The research demonstrates that integrating waste PET and crumb rubber in concrete mix is a sustainable practice. The output of this research can be used as a guideline for pavement researchers, engineers, designers, and end-users understanding the crucial microstructural and macro-characteristics of NRL-modified concrete with waste aggregates and can adjust the mix design to meet the specification requirements of the concrete for rigid pavement applications.

5.2 Recommendation

Despite good results, there were many errors in testing along the way. To get the best and accuracy outcome of hemp fiber reinforced concrete, there are some suggestions as follow:

I. Sand, crushed stone, and RCA must be tested and meet the requirement of Department of Highway, Thailand or follow ASTM standards to know the material properties for mix design which could affect the strength of concrete.

II. Sieving coarse aggregates in an appropriate percentage mixing of sizes could produce an accurate slump flow and density of the concrete.

III. Hemp fiber must be treated with 6% of sodium hydroxide (NaoH) to activate alkali in concrete which cleans the impurity and breaks down bundles to small individual fiber that can produce a better bonding in concrete.

IV. Water reduction admixture plays an important role to maintain the flow of concrete which recommended to mix as normal concrete to obtain a good mixture and follow adding hemp fiber in the last stage.

V. Water to cement ratio less than 0.45 is not recommended according to water absorption in hemp fiber could affect the water reactions in normal concrete and resulted in lower slump less than requirement.

VI. During mixing, avoid mixing at temperature higher than 30 degrees Celsius which affects the flow of the concrete. In addition, during casting in the mold, 3 layers of compaction must be followed to guarantee distribution greatly of hemp fibers in the samples.

VII. Before using PET and crumb rubber in mixing, cleaning the aggregate is a must to extract the dusty soil and unwanted waste particles.

VIII. Rubber latex must know the sources and check the property before using in the concrete.

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Yaowarat, T., Suddeepong, A., Hoy, M., Horpibulsuk, S., Takaikaew, T., Vichitcholchai, N., ... & Chinkulkijniwat, A. (2021). Improvement of flexural strength of concrete pavements using natural rubber latex. Construction and Building Materials, 282, 122704.

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APPENDIX A

LIST OF PUBLICATIONS

List of Publications

INTERNATIONAL JOURNAL PAPERS

M. Hoy, B. Ro, S. Horpibulsuk, A. Suddeepong, A. Buritatum, A. Arulrajah, M. Mobkrathok, A. Chinkulkijiniwat, and J. Horpibulsuk, (2023). Flexural fatigue performance of hemp fiber reinforced concrete using recycled concrete aggregates as a sustainable rigid pavement. International Journal Of Pavement Engineering (under review).

Samingthong, W., Hoy, M., Ro, B., Horpibulsuk, S., Yosthasaen, T., Suddeepong, A., ... & Arulrajah, A. (2023). Natural Rubber Latex-Modified Concrete with PET and Crumb Rubber Aggregate Replacements for Sustainable Rigid Pavements. *Sustainability*, 15(19), 14147.

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Article

Natural Rubber Latex-Modified Concrete with PET and Crumb Rubber Aggregate Replacements for Sustainable Rigid Pavements

Wisanukhorn Samingthong [1], Menglim Hoy [1,2,*], Bundam Ro [2], Suksun Horpibulsuk [1,2,3,4,5,*], Thanongsak Yosthasaen [4], Apichat Suddeepong [1,3], Apinun Buritatum [1,3], Teerasak Yaowarat [1,3] and Arul Arulrajah [6]

1 Center of Excellence in Innovation for Sustainable Infrastructure Development, Suranaree University of Technology, Nakhon Ratchasima 30000, Thailand
2 School of Civil Engineering, Suranaree University of Technology, Nakhon Ratchasima 30000, Thailand
3 School of Civil and Infrastructure Engineering, Suranaree University of Technology, Nakhon Ratchasima 30000, Thailand
4 Program in Civil Engineering and Construction Management, Suranaree University of Technology, Nakhon Ratchasima 30000, Thailand
5 Academy of Science, The Royal Society of Thailand, Bangkok 10300, Thailand
6 Department of Civil and Construction Engineering, Swinburne University of Technology, Melbourne, VIC 3122, Australia
* Correspondence: menglim@g.sut.ac.th (M.H.); suksun@g.sut.ac.th (S.H.)

Abstract: There are ongoing research challenges for the addition of the blend of PET and crumb rubber in polymer-modified concretes, which aims to leverage the benefits of both materials. In this study, various percentage combinations of waste aggregates, such as PET and crumb rubber, were used to replace coarse and fine aggregates in natural rubber latex (NRL)-modified concrete. Engineering properties such as compressive and flexural strengths, modulus of elasticity, and toughness obtained from compressive- and flexural stress-strain curves were investigated. Scanning electron microscopy (SEM) analysis was performed to examine the microstructural properties and study the strength development of the studied concretes. The results revealed that the compressive and flexural strengths of NRL-modified concretes with PET and crumb rubber aggregate replacements decreased with increasing replacement ratios. SEM analysis indicated that PET and crumb rubber (hydrophobic and non-polar materials) can affect the microstructure of the studied concrete by creating a weak interface between the aggregate and cement pastes, leading to reduced strength development. With the addition of the NRL additive, the film formation was found to act as a bridge and improve the bond strength of aggregates and hydration products in NRL-modified concrete. Furthermore, the integration of PET and crumb rubber aggregate can enhance the ability of the concrete to absorb energy and improve ductility. It was found that 10% of PET and crumb rubber aggregate replacement can be used for NRL-modified concrete as a rigid pavement, as its mechanical strengths satisfy the requirements set by the Department of Highways (DOH) in Thailand. This research helps repurpose waste materials and reduce the environmental footprint of concrete production.

Keywords: PET; crumb rubber; natural rubber latex; sustainable; concrete; pavement

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1. Introduction

Highways are important components of a nation's infrastructure and play an indispensable role in stimulating economic growth, enhancing connectivity, encouraging regional development, and elevating the standard of living [1–4]. The construction of pavements involves a series of layered components, such as a subbase, base, and surface course, each with a specific role. The subbase, which sits directly atop the prepared natural ground level or subgrade, is usually composed of locally sourced materials or stabilized soil. It is designed to evenly distribute the load from the base to the subgrade, effectively safeguarding the impact of aggressive moisture. The base layer above the subbase often consists of crushed aggregate designed to further distribute the load, thereby providing a stable surface for the subsequent pavement layer and protecting the underlying subbase from detrimental environmental effects. The surface course is constructed using high-quality materials such as asphalt or concrete, ensuring its ability to resist traffic loads and provide a durable and skid-resistant surface, making it critical for safety and efficiency in transportation. Based on the type of surface course, the pavement can be classified into two categories: flexible pavement (asphalt surface layer) and rigid pavement (concrete surface layer). Because of their rigidity, the load on rigid pavements is distributed over a wide area of the subgrade. This reduces the stress on the subgrade and makes the pavement more tolerant to weaker or less uniformly compacted subgrades when compared with the flexible pavement. In addition, rigid pavements are resistant to rutting and weathering and require less maintenance over time [5–7].

Rigid pavements are primarily made from a mix of cement, coarse and fine aggregates, and water. In addition, the admixture is incorporated into the mix to modify concrete properties. Portland cement is the binding agent in the concrete mix. When mixed with water, it reacts chemically to form a hard, strong, and durable matrix, which binds the aggregate particles together. In concrete paving materials, a significant source of greenhouse gas emissions is the cement manufacturing process [8,9]. The production of Portland cement is a process that emits a lot of greenhouse gases, as it relies on burning fossil fuels for its energy. In a cement kiln, limestone (calcium carbonate) and clays are heated to very high temperatures (about 1400–1450 °C) to produce clinker, the main component in Portland cement. Throughout the manufacturing process, calcination can generate approximately 7% of CO_2 [10]. This has led to an increasing interest in developing alternative cementitious materials and production methods that are more sustainable. Because of the low-temperature production methods, hydraulic cement is reported to have a lower carbon footprint than conventional Portland cement [11].

Coarse and fine aggregates are crucial components in the concrete mix. The coarse aggregate provides bulk, strength, and wear resistance to the pavement, while the fine aggregate (typically sand) fills the spaces between the coarse aggregate, makes it more cohesive, and prevents the concrete from shrinking and cracking. In recent years, environmental and sustainable considerations have led to the inclusion of recycled materials and additives in the concrete layer to improve performance and reduce the environmental impact [12–14]. The environmental issues associated with the disposal of used tires and PET plastic are substantial, which cause negative impacts on the environment and may result from improper management of these materials. The production of plastic waste is a significant issue, with millions of tons produced annually [15]. Due to their slow decomposition and incorrect disposal, PET plastic bottles add to the rising problem of plastic waste by taking up landfill space and increasing the risk of microplastic pollution [16,17]. Similarly, a large amount of waste tires is generated every year and poses long-term environmental risks since they take up valuable landfill space and do not biodegrade [18–20]. Poorly managed waste tires can pose safety issues, attract bugs, and discharge harmful materials into the ground and water [21–23].

In recent years, there have been significant developments in the field of sustainable construction materials, such as innovation involving the incorporation of PET plastics and waste tires in concrete pavement [24,25]. Waste can be made into crumb rubber particles and used in the concrete mix as a sand replacement [26]. Utilizing crumb rubber reduces the need for sand mining, protects natural resources, and lessens its negative effects on the environment. PET plastic bottles can also be broken down into small particles and utilized as alternative aggregates in the concrete mix [27]. However, the utilization of PET and waste tires in the concrete mix resulted in a reduction of its flexural strength, which is a vital property for concrete pavement. Therefore, additional additives might enhance the properties of concrete in rigid pavement applications. A synthetic latex polymer, namely Styrene-Butadiene Rubber (SBR), is highly regarded for its good resistance to abrasion and durability. When added to concrete, SBR latex can enhance the adhesive strength between the aggregate and cement paste, making the concrete more resistant to mechanical stress and reducing the risk of cracking. Basalt fibers are a type of reinforcement that can prevent the post-cracking of concrete. The combination of SBR latex and basalt fibers in concrete can therefore create a highly durable material with excellent post-cracking behavior [28,29]. In terms of sustainable road construction, Yaowarat et al. proposed an innovative idea of value-added NRL, a polymer additive and studied the effect of various rubber-to-cement (r/c) ratios on the strength development of normal concrete [30]. It indicated that the optimum r/c ratio could improve the modulus of rupture of the concrete, resulting in the durability of the roadway.

To the authors' best knowledge, the evaluation of using NRL to improve the strength characteristics of concrete with crumb rubber (CR) and PET as aggregate replacement is still limited; hence, it is the aim of this research work. The experimental testing, including compressive and flexural strength, was conducted to investigate the mechanical strength development of concretes with various PET and CR replacement ratios and an optimum r/c ratio. The toughness and resilient modulus of the studied mixtures were also evaluated. Scanning electron microscopy (SEM) was used to examine the microstructure and evaluate the strength development of the studied concrete. SEM was used to investigate the particle interaction within the concrete matrix in order to gain knowledge about the composite's overall efficacy and pinpoint areas for development.

The results of this study will advance understanding of the mechanical characteristics of concretes containing PET plastic and crumb rubber. It will offer useful knowledge for the development of sustainable construction methods and the incorporation of recycled aggregates in the concrete mixture. This study's ultimate goals are to encourage recycling, lessen trash production, and propose a more circular and environmentally friendly method of designing and building rigid pavements.

2. Materials and Methods

2.1. Materials

The research used hydraulic cement with a specific gravity of 3.15. The properties of the studied polymer additive are illustrated in Table 1. It was obtained from the Rubber Authority of Thailand and contained 52% dry rubber, 48% water, and water-soluble components. The pH was tested to ensure the acidity content in the rubber controlled the property for the other tests, which equaled 10.4.

Table 1. Physical properties of Natural Rubber Latex (NRL).

Properties	*Value*
pH value	10.4
Dry rubber (%)	52.0
Water and water-soluble components (%)	47.3
Ammonia (%)	0.69

Table 2 shows the properties of coarse aggregate (crushed rock) and fine aggregate (natural river sand). The concrete specimens were prepared in accordance with ASTM C127 and ASTM C128 [31,32]. The nominal maximum size of 19 mm of the coarse aggregate was used in this study. The specific gravity of the coarse aggregate was 2.70, while that of the fine aggregate was 2.66. The coarse and fine aggregates had water absorptions of 1.85% and 0.74%, respectively. The fineness modulus and the percent of voids in the fine aggregate were 2.70 and 38.24, respectively. The coarse aggregate had a Los angles abrasion loss, a flakiness index, and an elongation index of 22.2%, 27.69%, and 22.35%, respectively. The waste tires were crushed by a tire granulator crusher machine, resulting in a granular size between 2 and 3 mm to replace the sand with a specific gravity of 1.02. While PET bottles were collected, pre-washed, and shredded by a plastic shredder machine into granules with an average size of 10 mm to replace the crushed stone, the specific gravity was 1.20 [33]. Thus, there was a mixture between the crumb rubber and PET in concrete proportions to reduce the fine and coarse aggregates. The particle sizes were sieved and controlled by ASTM C33 and ASTM C136 [34,35], which limited the lower and upper boundaries in Figure 1. The figure showed the mixture between sand and crushed stone and the combination between PET and crumb rubber in various percentage mixtures.

Table 2. Basic physical and engineering properties of NRL, fine, and coarse aggregate.

Properties	*Value*
Coarse Aggregate	
Maximum size aggregate (mm)	19.0
Saturated surface dry specific gravity	2.70
Dry specific gravity	2.47
Dry rodded density (kg/m^3)	1630
Absorption (%)	1.85
Moisture content (%)	1.02
Abrasion loss (%)	22.2
Flakiness index (%)	27.7
Elongation Index (%)	22.4
Fine Aggregate	
Saturated surface dry specific gravity	2.65
Dry specific gravity	2.60
Percentage of voids (%)	38.2
Dry unit density (kg/m^3)	1604
Absorption (%)	0.74
Moisture content (%)	2.46
Fineness modulus	2.70
Crumb Rubber	
Appearance	Black and Rough
Particle size (mm)	2–3
Dry specific gravity	1.02
Water absorption (%)	1.05
Melting point (°C)	196
PET	
Appearance	Round and Smooth
Particle size (mm)	9–10
Specific gravity	1.20
Water absorption (%)	0.02
Melting point (°C)	255

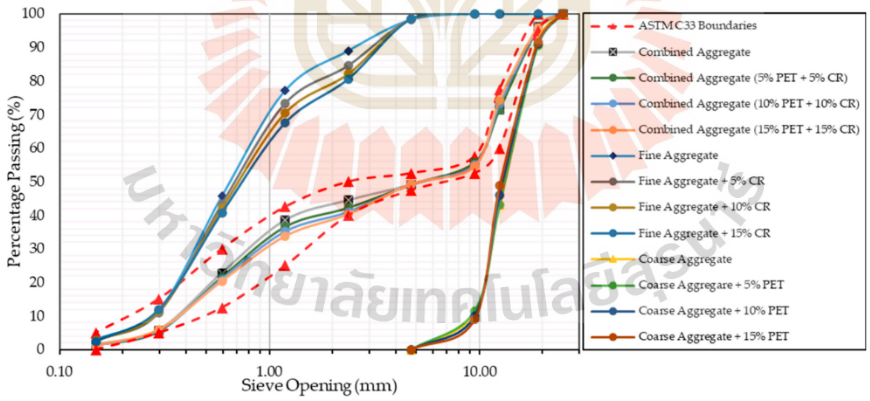

Figure 1. Grain size distribution of coarse and fine aggregate.

2.2. Concrete Mix Design

Earlier research reported that the w/c ratio is a key determinant of the strength of concrete, i.e., a lower w/c ratio can lead to higher-strength concrete [30,36]. However, a lower w/c ratio often requires a higher cement content, leading to an increase in the cost of the concrete mix and an environmental burden. Therefore, a balanced approach considering cost, performance, and a sustainable solution is crucial in the concrete mix design. The w/c ratio was fixed at 0.5 for all studied samples, whereas the r/c ratio was fixed at 0.58 for NRL-modified concrete and NRL-modified concrete with PET and crumb rubber replacements.

$$\text{Natural Rubber Latex, } NRL = ((r/c)/100)\, C \tag{1}$$

$$\text{Water Content in NRL, } W_{NRL} = 0.48\, NRL \tag{2}$$

$$\text{Total Water Used, } W_t = W_D - W_{NRL} \tag{3}$$

where r/c = rubber-to-cement ratio (%), C = cement (kg), W_{NRL} (kg), and W_t (kg).

These ratios were selected to study based on previous research and practical work, which were reported to be the optimum ratios for producing concrete pavement that meets the minimum required compressive and flexural strengths set by the DOHs in Thailand [36]. The amount of NRL can be determined following Equations (1)–(3), which relate to a water content of 48% in total natural rubber latex, according to Yaowarat et al. [30].

In this study, the slump value for the studied concrete mixes was in control at 75 mm ± 25 mm for the concrete pavement application. To examine the influence of PET and CR on the compressive and flexural strengths of the studied mixes, the combination of PET and CR was designed to substitute coarse and fine aggregates, respectively, in percentages of 5%, 10%, and 15%. Therefore, a total of 4 mixes, as shown in Table 3, were studied in this research (i.e., normal concrete, NRL-modified concrete, NRL10WP = a blend of 5% crumb rubber and 5% PET, NRL20WP = a blend of 10% crumb rubber and 10% PET, and NRL30WP = a blend of 15% crumb rubber and 15% PET).

Table 3. Mixing proportion of fresh concrete.

Mix Ingredients	*Mix ID*	*w/c*	*Cement* (kg/m^3)	*Water* (kg/m^3)	*F.A.* (kg/m^3)		*C.A.* (kg/m^3)		*NRL* (kg/m^3)
					Sand	*CR*	*NCA*	*PET*	*r/c* = 0.58
Normal Concrete	Control	0.50	385	192.5	745	0	1052	0.0	0.00
NRL (*r/c* = 0.58%)	NRL	0.50	385	191.4	745	0	1052	0.0	2.23
5% *PET* + 5% *CR* + 0.58% *NRL*	NRL10WP	0.50	385	191.4	708	37	999	53	2.23
10% *PET* + 10% *CR* + 0.58% *NRL*	NRL20WP	0.50	385	191.4	671	75	947	105	2.23
15% *PET* + 15% *CR* + 0.58% *NRL*	NRL30WP	0.50	385	191.4	633	112	894	158	2.23

2.3. Experimental Testing Program

2.3.1. Compressive and Flexural Strengths

The fresh concrete was prepared following ASTM C192 [37] and then placed in the cylindrical (150 mm × 300 mm) molds for the compressive strength test as per ASTM C39 [38] and prismatic molds (150 mm × 150 mm × 600 mm) for the flexural strength test as per AASHTO T97 [39]. The mixture was placed in three separate stages, and each layer was compacted using a standard tamping rod with 25 strikes. After being cured at room temperature for a day, the samples were then demolded and placed in water maintained at a temperature of 27 °C ± 2 °C. They were kept submerged for periods of 7, 14, and 28 days prior to the compressive and flexural tests. The procedure for the compressive strength test was implemented as per the ASTM C39 standard, while the flexural strength test adhered to the AASHTO T97, employing the third-point loading technique. The flexural strength (f_f) was computed using the following expression:

$$f_f = \frac{PL}{bd^2} \tag{4}$$

where P represents the maximum load applied to the sample; L denotes the length of the support; and b and d are the average width and depth of the beam specimen, respectively.

The tested data were analyzed in the mean value of test specimens within the same testing condition in compression and flexural strengths to secure reliable data, followed by a low mean standard deviation, SD (SD/x < 10%, where x is the mean strength value).

2.3.2. Scanning Electron Microscopy (SEM)

The effect of various replacement materials, such as NRL, PET, and crumb rubber, on the strength developments was examined using SEM analysis. Fragments from the specimen strength tested after 28 days were used to perform SEM analysis. To prevent the hydration of the samples, they were first frozen and dried, and then coated with gold before conducting SEM analysis. SEM morphological detection at 1000 and 5000 times magnification was performed.

3. Results and Discussion

3.1. Compressive Strength

The compressive strengths of the studied samples cured at all curing periods are shown in Figure 2. The solid red line demonstrates the minimum 28-day compressive strength requirement ($f_c \geq 32$ MPa) for concrete pavement set by the DOH, Thailand [40]. For normal concrete (a controlled sample), the 7, 14, and 28-day compressive strengths were 27.6, 34.3, and 38.8 MPa, respectively, which is a common strength development of concrete. It implies that the compressive strength developed by increasing curing time. As expected, when NRL additive was added to the concrete, the compressive strength of the NRL-modified concrete was reduced when compared with the control concrete, which was similar to the previous research [30,36]. Umasabor and Daniel [41] examined the influence of various percentages of PET replacement on the compressive strength of concrete. It was found that PET at 5% by weight was the optimum value and provided the highest compressive strength of concrete. Chong and Shi [42] performed a statistical analysis based on 100 data sets to study the use of PET plastics as concrete fine and coarse aggregates and revealed that concrete containing up to 30% PTE replacement can be sustainable and have minimal strength reduction. The 7, 14, and 28-day compressive strengths of NRL-modified concrete were 24.6, 29.6, and 34.3 MPa, respectively. The compressive strength of the NRL-modified concrete with waste aggregate replacements decreased with increasing aggregate replacement ratios and was lower than that of normal concrete and NRL-modified concrete, respectively. The findings of this study are consistent with the results of previous research on the effects of waste PET bottles and crumb rubber aggregates on the hardened properties of concrete [27,43,44]. However, the NRL10WP sample (NRL-modified concrete with 5% PET + 5% crumb rubber aggregate) had compressive strength at 28 days greater than the requirement for a concrete pavement designated by DOHs in Thailand. The compressive strength of NRL10WP was 21.9 MPa, 28.77 MPa, and 32.5 MPa at 7, 14, and 28 days, respectively. In other words, the compressive strength was found to be reduced by 8.3% compared to that of NRL-modified samples. The compressive strength of NRL20WP was approximately 15% lower than that of NRL-modified concrete. The compressive strength was found to be remarkably reduced when the waste aggregate replacement in the NRL-modified concrete was 30%. The 7, 14, and 28-day compressive strengths of NRL30WP were 13.6, 22.3, and 24.5 MPa, respectively. The 28-day compressive strength of NRL30WP indicated 28.5% and 36.9% in strength reduction when compared to the NRL-modified concrete and normal concrete, respectively.

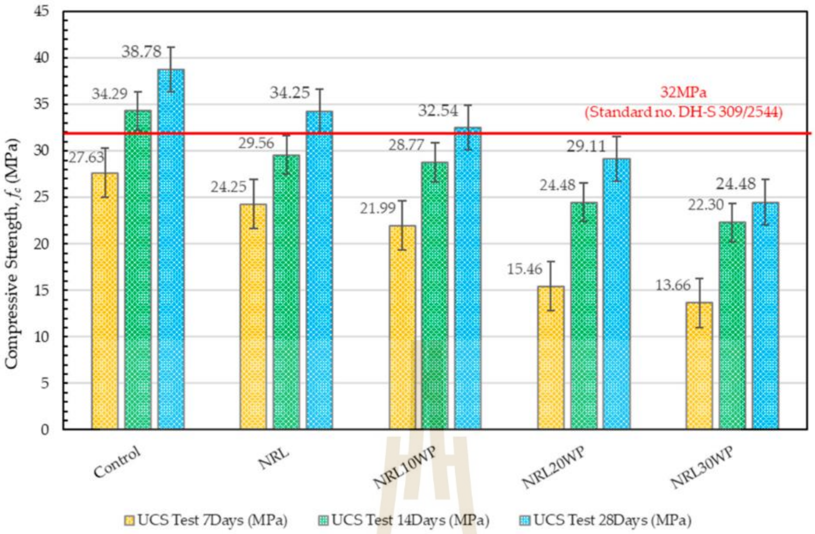

Figure 2. Compressive Strength Development of Waste Polymer Concrete.

3.2. Flexural Strength

The flexural strengths of the control samples, NRL-modified concrete, and NRL-modified waste polymer concrete samples cured at 7, 14, and 28 days are shown in Figure 3. The solid line indicates the minimum 28-day flexural strength requirement ($f_f \geq 4.2$ MPa) for concrete pavement specified by DOH, Thailand [40]. For normal concrete, the flexural strength increased with curing time as expected; flexural strength initially was 2.8 MPa at 7 days, 4.3 MPa at 14 days, and 4.7 MPa at 28 days, which met the specification. These values are commonly reported for normal concrete.

Figure 3 demonstrates that the NRL polymer can enhance the flexural strength of NRL-modified concrete, and its 28-day flexural strength was about 3.3% higher than that of normal concrete. The flexural strength of NRL-modified concrete was 2.9, 4.3, and 4.86 MPa at 7, 14, and 28 days, respectively. This is because the NRL modifies the microstructure of the concrete, making it denser and reducing the gaps between particles, which prevents water alteration in the matrix and modifies the chemical reaction phases [30,36]. The influence of the PET and crumb rubber aggregate replacement was found to reduce the flexural strength when compared with normal concrete.

The flexural strength of concrete with PET and crumb rubber aggregate replacement decreased with increasing replacement ratios. Although the flexural strength was reduced, the 28-day flexural strength of NRL10WP was 4.4 MPa, which met the minimum requirement of 4.2 MPa.

Furthermore, at the age of 28 days, the flexural strength of NRL10WP, NRL20WP, and NRL30WP concretes was respectively 5.2%, 24.9%, and 36.9% lower than that of normal concrete. The percentage reduction in flexural strength of NRL10WP was lower than that of concrete using PET or crumb rubber aggregate as a rigid pavement previously reported [22]. This implies that NRL additives can improve the flexural strength development of NRL-modified concrete with PET and crumb rubber aggregate replacement.

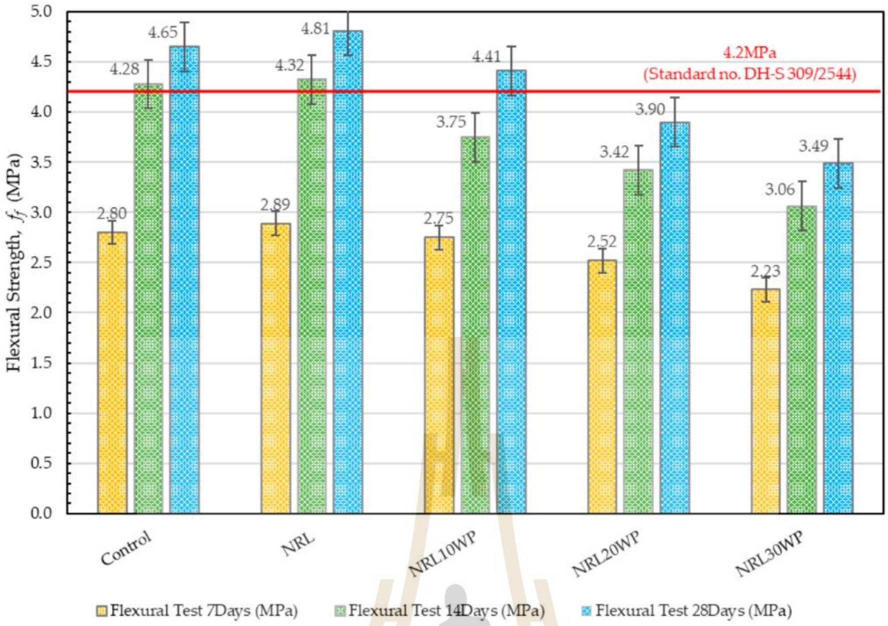

Figure 3. Flexural Strength Development of Waste Polymer Concrete.

The modulus of elasticity (Young's modulus) of the studied concrete in Table 4 was obtained from the compressive stress-strain curve at 28 days, as shown in Figure 4. In general, the Young's modulus of the normal concrete was in the range of 30 and 50 GPa, and the Young's modulus of the studied control sample was 33.91 GPa. The Young's modulus of the NRL-modified sample was approximately 28.4% lower than the control sample. While the Young's modulus of NRL-modified samples with PET and crumb rubber aggregate replacement remarkably decreased with the increase in replacement ratios, the modulus of elasticity of NRL10WP, NRL20WP, and NRL30WP was 20.4, 16.2, and 13.04 GPa, respectively.

Table 4. Mechanical properties of waste polymer concrete.

Mix ID	*Density* Kg/m^3	*Modulus of Elasticity* GPa	*Flexural Toughness* MPa·m	*Compressive Toughness* MJ/m^3
Control	2386.4	33.91	1.29	5.35
NRL	2385.2	24.27	1.65	4.48
NRL10WP	2342.3	20.37	1.81	4.74
NRL20WP	2325.6	16.18	1.89	4.30
NRL30WP	2305.4	13.04	2.02	4.22

The compressive toughness was used to demonstrate the energy absorption in the compressive mode. The compressive toughness (measured in MJ/m^3) of the studied samples can be determined from their compressive stress-strain curve depicted in Figure 4. The compressive toughness of the control sample was 5.35 MJ/m^3, while the NRL-modified sample had a compressive toughness of 4.89 MJ/m^3, or about 8.6% lower than the normal concrete. The compressive toughness of NRL10WP, NRL20WP, and NRL30WP was 4.74, 4.30, and 4.22 MJ/m^3, respectively. In other words, the toughness of the NRL-modified sample was about 11.4%, 19.6%, and 21.1% with 10%, 20%, and 30% of PET and crumb rubber aggregate replacement, respectively, lower than the control sample.

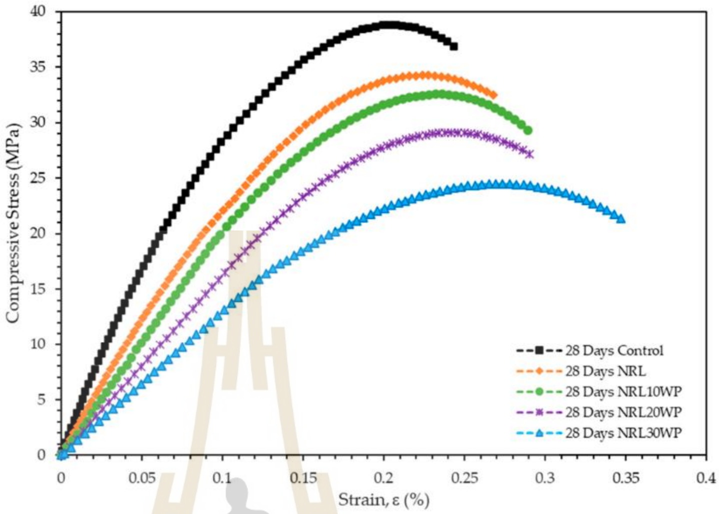

Figure 4. Compressive stress-strain curves of the studied concrete samples curing at 28 Days.

On the other hand, the flexural toughness characteristics of NRL-modified concrete with and without PET and crumb rubber replacement were found to be different from their compressive toughness. The flexural toughness is used to indicate the energy absorption of the studied concrete when subjected to bending stress, such as traffic loading on the concrete slab. The bending stress generated by repeated traffic loading can cause distress in the rigid pavement, which is considered the major mode of failure of concrete pavement. Therefore, the concrete's ability to absorb energy (fracture energy), also known as flexural toughness, can positively impact the service life of a rigid pavement. This characteristic allows the pavement to resist crack propagation better, which is particularly important considering the dynamic loads and environmental impacts pavements are subjected to [45].

When the concrete has a higher energy absorption capacity, it can deform more before fracturing. This deformation distributes stresses over a large volume of the material, which can prevent or delay the initiation of cracks. Furthermore, even when cracks do start, the higher energy absorption capacity can help prevent the rapid growth of these cracks [46]. As such, it increases the pavement's durability and resilience against various forms of distress, potentially extending its service life.

The values of the flexural toughness of the studied concrete samples summarized in Table 4 were determined in MPa.m. and obtained from their flexural stress-strain curves, as depicted in Figure 5. It clearly indicated that the energy absorption of the NRL-modified concrete (1.65 MPa·m) was higher than that of normal concrete (1.29 MPa·m). This confirms that the addition of an NRL additive can enhance the flexural strength and energy absorption capacity of normal concrete. Even though the flexural strength values of the NRL-modified concrete with PET and crumb rubber aggregate replacement were lower than those of normal concrete, their flexural toughness values were higher than those of normal concrete. In addition, the energy absorption capacity of the NRL-modified concrete with waste aggregate replacement increased with the increase in replacement ratios. It implies that the NRL-modified concrete with PET and crumb rubber aggregate replacement had better ductility behavior than that of the normal concrete.

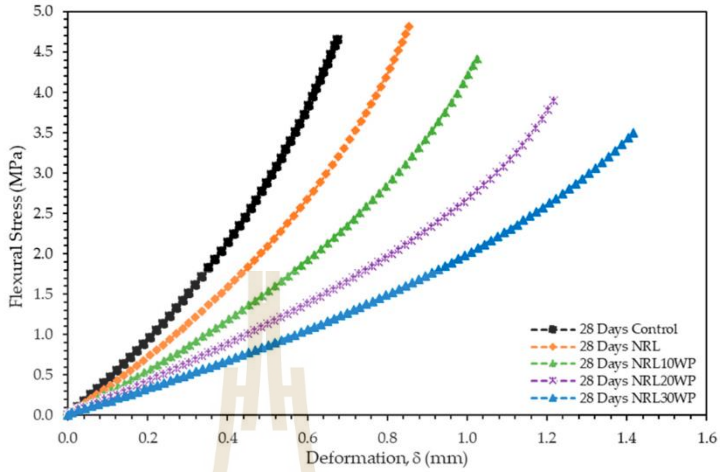

Figure 5. Flexural stress-strain curves of the studied concrete samples curing at 28 Days.

The flexural and compressive strengths are crucial parameters in concrete material selection for rigid pavement application because they determine how much load a material or pavement structural layers can withstand without deforming or failing in both compressive and tensile modes. The relationship between the two is important because it helps pavement engineers or designers predict how a material will behave under different types of stress. In other words, a normal concrete material may have high compressive strength but low flexural strength, meaning it can withstand being compressed but may easily fracture when subjected to tensile stress. This is significant in applications such as rigid pavement, where both compression and bending forces are present; hence, the relationship between the flexural and compressive strengths of normal concrete is generally plotted.

The relationship between the flexural strength (f_f) and compressive strength (f_c) of the NRL-modified concrete with PET and crumb rubber aggregate replacement is plotted in Figure 6. The dashed red line shows the normalize of the studied concrete mixes. This relationship can help pavement engineers or designers choose waste materials such as PET and crumb rubber for a specific application and design safer, more efficient structures. It can also be used in quality control, failure analysis, and the development of new waste materials. In addition, a common assumption in concrete pavement design is that the modulus of elasticity of concrete is directly related to its compressive strength. This implies that as the compressive strength of the concrete increases, so does its stiffness. Therefore, the relationship between the modulus of elasticity and the compressive strength can be used to predict the performance of concrete under various load conditions. This relationship is not always linear or direct, and it can be influenced by several factors, such as the type and quantity of aggregate used in the mix. As such, the actual tests on the concrete are required to determine these properties accurately for pavement structural design applications.

Figure 7 shows the relationship between modulus of elasticity (E_c) and 28-day compressive strength (f_c) of NRL-modified concrete with PET and crumb rubber aggregate replacement. The relationship between these two properties can help in optimizing the NRL-modified concrete mix design when waste PET and crumb rubber are used as aggregate replacements. By adjusting the ingredients and proportions in the mix, one can control both compressive strength and the modulus of elasticity to meet the specific requirements of a rigid pavement design. The dashed red line indicates the boundary between the normal concrete and the NRL-modified concrete with PET and crumb rubber aggregates replacement.

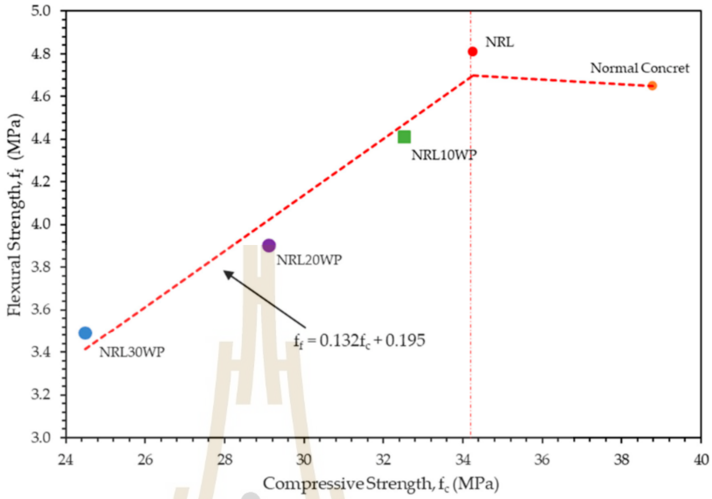

Figure 6. Relationship between compressive and flexural strength at 28 days.

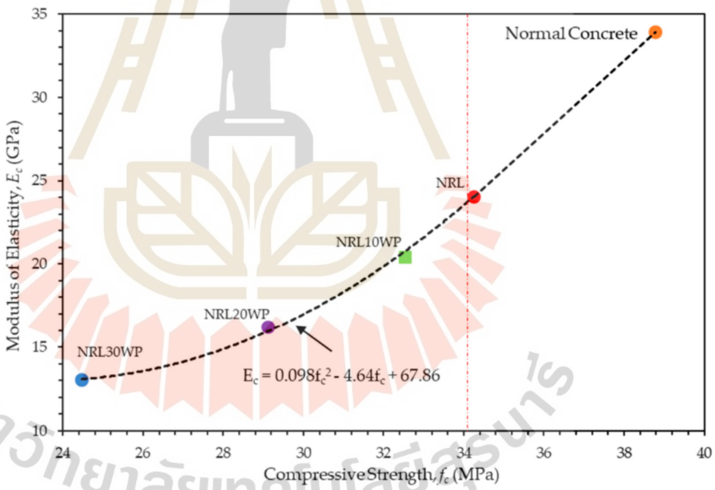

Figure 7. Relationship between compressive strength and modulus of elasticity at 28 days.

3.3. Microstructural Analysis

SEM analysis is a powerful tool for examining the microstructural properties of concrete, including cement hydration products, aggregate properties, the Interface Transition

Zone, microcracks, and the pore structure. These insights help understand concrete's performance, including its mechanical properties and durability [47,48]. Figure 8 illustrates the SEM images of normal concrete, NRL-modified concrete, NRL10WP, and NRL30WP, which were cured for 28 days at magnifications of 1000 and 5000 times, respectively. In Figure 8a, plenty of C-S-H gel, $Ca(OH)_2$, and ettringite were evidently identified in the control sample (without NRL and waste aggregates). This confirmed that the strength of the concrete was theoretically developed in accordance with the production of hydration products.

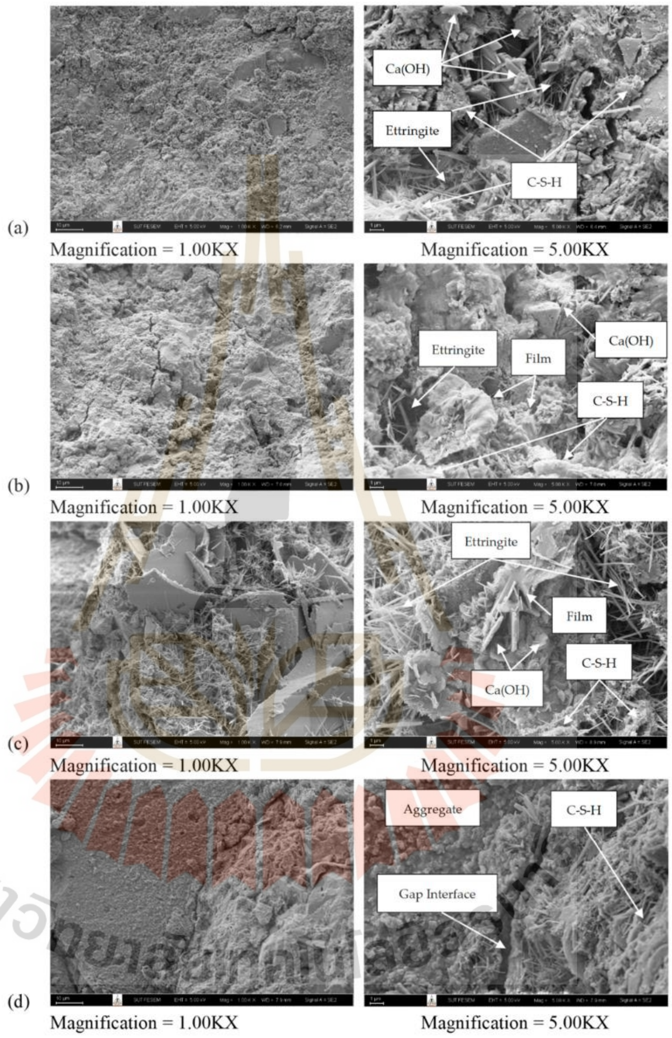

Figure 8. SEM image of: (**a**) Normal Concrete, (**b**) NRL-modified concrete, (**c**) NRL10WP, and (**d**) NRL30WP.

Figure 8b shows the SEM images of NRL-modified concrete, which demonstrated that its matrix became slightly loose compared to the normal concrete. This might be due to the effect of the NRL additive-generated film network blocking the growth of hydration products, which resulted in lower compressive strength. However, the film network was detected to be covering and bridging the C-S-H gels and aggregates. Furthermore, less ettringite was detected, resulting in enhanced adhesion or bonding between the aggregates by the film network. Therefore, the flexural strength of the NRL-modified concrete was increased [25,32]. In addition, the NRL film network can absorb energy and help mitigate crack propagation in the concrete, which reduces the likelihood of a brittle failure. This confirmed the improvement of concrete's toughness and ductility, as demonstrated in Figure 5. Figure 8c illustrates the SEM images of NRL-modified concrete with 10% PET and crumb rubber aggregate replacement (NRL10WP). It clearly indicated that the connection between the waste aggregates and hydration products resulted in several pores and a loose matrix. This led to a reduction in its compressive and flexural strengths. An SEM image of NRL-modified concrete with 30% PET and crumb rubber aggregate replacement (NRL30WP) was demonstrated in Figure 8d.

It was evident that the higher rate of crumb rubber and PET replacement affected the microstructure by creating a brittle interface between the aggregate and the cement paste. PET and crumb rubber are hydrophobic and non-polar materials, which make them difficult for the cement paste to bond with. Subsequently, this can lead to a remarkable reduction in compressive strength. However, the inclusion of crumb rubber and PET can increase the concrete's ability to absorb energy, improving its toughness and resistance to impact and dynamic loads due to its plastic deformation characteristics [41].

The use of waste PET and crumb rubber in NRL-modified concrete is a sustainable practice that can alter the microstructure and mechanical properties of the concrete when used in rigid pavement applications. However, it is crucial to consider the specific requirements of the concrete and adjust the mix design accordingly to attest to the best possibility of using these waste aggregates in concrete pavement applications.

4. Conclusions

This research investigates the effect of waste PET and crumb rubber aggregate replacement on the microstructure and strength characteristics of NRL-modified concrete. The combination of PET and crumb rubber in percentages of 10%, 20%, and 30% aggregate replacement ratios was studied. With the addition of the NRL additive, the compressive strength of the NRL-modified concrete was lower than that of the normal concrete. At the age of 28 days, the compressive strength of NRL10WP, NRL20WP, and NRL30WP was about 8.3%, 15%, and 28.5% lower than that of NRL-modified concrete. On the other hand, the flexural strength of NRL-modified concrete was approximately 3.3% higher than normal concrete. While the NRL-modified concrete with PET and crumb rubber aggregate replacement indicated a reduction in flexural strength with the increased replacement ratio, the flexural strength of NRL10WP was found to meet the minimum flexural strength requirement ($f_f \geq 4.2$ MPa) for rigid pavement specified by DOH, Thailand. Microstructural analysis indicated that the addition of NRL additive generated the film network to prevent the development of hydration products and resulted in a compressive strength reduction. However, this film network acts as a bridge mechanism to reinforce the adhesion between the aggregates in the concrete matrix, leading to improved flexural strength. PET and crumb rubber are hydrophobic and non-polar materials; hence, increasing the amount of these materials in the concrete mix can affect their microstructure by creating weaker interfaces between aggregates and cement paste. As such, the mechanical strength dropped. However, the PET and crumb rubber aggregate replacement can improve the ability to absorb energy in NRL-modified concrete and hence improve its toughness and resistance to impact and dynamic loads.

The research demonstrates that integrating waste PET and crumb rubber into concrete mixes is a sustainable practice. In terms of mechanical strength properties, it is confirmed that

10% of waste PET and crumb rubber aggregate replacement can be used in concrete mix for rigid pavement design. The output of this research can be used as a guideline for pavement researchers, engineers, designers, and end-users to understand the crucial microstructural and macro-characteristics of NRL-modified concrete with waste aggregates and adjust the mix design to meet the specification requirements of the concrete for rigid pavement applications. Ultimately, a combination of lab-scale research, field trials, and close collaboration between researchers and practitioners is required to successfully develop and implement this new material and techniques in the field of concrete technology. Hence, field trials to validate the lab results under more realistic conditions are recommended for future research.

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Abbreviations

C-S-H	Calcium silicate hydrate
CR	crumb rubber
f_c	compressive strength
f_f	flexural strength
NRL	Natural rubber latex
PET	Polyethylene terephthalate
r/c	rubber-to-cement ratio
SBR	Styrene-butadiene rubber
SEM	Scanning electron microscopy
W_{NRL}	Water content in natural rubber latex

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BIOGRAPHY

Mr. Bundam Ro, born on July 4, 1998, in Siem Reap, Cambodia, began his educational journey at Wat Boo Primary School, followed by 10 January 1979 High School. He received a partial scholarship to attend Future Bright International School, where he graduated with a strong Grade B+ (GPA 3.25) in grade 12. In 2017, he was awarded a Royal Scholarship, enabling him to pursue a bachelor's degree in civil engineering international program at Suranaree University of Technology, where he excelled with a GPAX of 3.49. During his undergraduate years, he actively participated in international events and completed a global project-based learning experience in Japan. During his bachelor's degree, he gained practical experience with Frontier Real Estate Company, Supalai Public Company Limited Co., Ltd. His passion for geotechnical engineering led him to pursue a master's degree, supported by the Veithedbandith Scholarship in 2021. During his postgraduate studies, he served as an assistant lecturer, gaining valuable teaching experience. His research efforts resulted in the publication of a paper in Sustainability journal, titled "Natural Rubber Latex-Modified Concrete for Sustainable Rigid Pavements." Another paper, focusing on "Fatigue Performance of Hemp Fiber Reinforced Concrete Using Recycled Concrete Aggregate as a Sustainable Rigid Pavement." is currently awaiting submission to International Journal of Pavement Engineering. With a strong educational foundation, a passion for geotechnical engineering, and a commitment to research and teaching, He aspires to become a dedicated lecturer and make a significant impact in the field of civil engineering.