การประเมินคุณสมบัติทางกายภาพและเทคนิคธรณีของส่วนผสมระหว่างมวลรวมรีไซเคิลและหินคลุก

นายซีไรรวช เจีย

วิทยานิพนธ์นี้เป็นส่วนหนึ่งของการศึกษาตามหลักสูตรปริญญาวิศวกรรมศาสตรมหาบัณฑิต

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ปีการศึกษา 2557

ASSESSMENT OF PHYSICAL AND GEOTECHNICAL PROPERTIES OF RECYCLED CONCRETE AGGREGATE AND CRUSHED ROCK BLENDS

Sereyroath Chea

A Thesis Submitted in Partial Fulfillment of the Requirements for the Degree of Master of Engineering in Civil Engineering

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ASSESSMENT OF PHYSICAL AND GEOTECHNICAL PROPERTIES OF RECYCLED CONCRETE AGGREGATE AND CRUSHED ROCK BLENDS

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

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ซีไรรวช เจีย : การประเมินคุณสมบัติทางกายภาพและเทคนิคธรณีของส่วนผสมระหว่างมวลรวมรีไซเคิลและหินคลุก (ASSESSMENT OF PHYSICAL AND GEOTECHNICAL PROPERTIES OF RECYCLED CONCRETE AGGREGATE AND CRUSHED ROCK BLENDS) อาจารย์ที่ปรึกษา : ศาสตราจารย์ ดร.สุขสันติ์ หอพิบูลสุข, 88 หน้า

ปัจจุบันทั่วโลกได้ตระหนักถึงปัญหาด้านสิ่งแวดล้อม และได้มีการผลักดันให้มีการแก้ไขปัญหาอย่างต่อเนื่อง ซึ่งรวมถึงการหาวิธีเพื่อนำวัสดุเหลือใช้กลับมาใช้ใหม่ การศึกษานี้มีวัตถุประสงค์เพื่อตรวจสอบคุณสมบัติทางกายภาพและทางธรณีเทคนิคของมวลรวมคอนกรีต รีไซเคิล (RCA) ผสมหินคลุก (CR) สำหรับการใช้เป็นวัสดุผิวทาง โดยกำหนดให้อนุภาคของ RCA และ CR มีขนาดที่ใกล้เคียงกัน และและมีขนาดตามข้อกำหนดของกรมทางหลวงของประเทศไทย การทดลองในห้องปฏิบัติการประกอบไปด้วยการวิเคราะห์การกระจายขนาดของอนุภาค ความหนาแน่นของอนุภาค การดูดซึมน้ำ ความสึกหรอจากเครื่องลอสแอนเจลิส *(LA)* อัตราส่วนแคลิฟอร์เนียแบริ่ง (CBR) และกำลังต้านทานแรงเฉือนด้วยวิธีแรงเฉือนโดยตรง RCA และ CR ได้ถูกผสมเป็นตัวอย่างการทดสอบ ในอัตราส่วนการแทนที่ RCA 0% 30% 50% 70% และ 100% ของมวลรวมทั้งหมด ผลการศึกษาพบว่า การเพิ่มขึ้นของปริมาณของ RCA ส่งผลให้ความชื้นที่เหมาะสม (OWC) เพิ่มขึ้น เนื่องจากอนุภาคของ RCA มีค่าการดูดซึมน้ำสูง เนื่องจากอนุภาค RCA มีความแข็งแรงต่ำ การเพิ่มปริมาณ RCA จึงมีผลให้ความสึกหรอเพิ่มขึ้น ส่วนผสมระหว่าง RCA และ CR ที่อัตราส่วนการแทนที่ด้วย RCA ระหว่างร้อยละ 30 และ 100 สามารถใช้เป็นวัสดุรองพื้นทางได้ ซึ่งความสึกหรอมีค่าระหว่างร้อยละ 17-39 การดูดซึมน้ำมีค่าระหว่างร้อยละ 2.4-4.2 และ CBR มีค่าระหว่างร้อยละ 36-128 กำลังรับแรงเฉือนสูงสุดของส่วนผสม RCA และ CR มีค่าลดลงเมื่อ RCA มีประมาณเพิ่มขึ้น tan ϕ_p มีค่าระหว่าง 0.52-1.00 สำหรับอัตราการแทนที่ของ RCA ตั้งแต่ร้อยละ 0 ถึง 100 การศึกษาครั้งนี้ได้เสนอความสัมพันธ์ระหว่างค่าความสึกหรอ ความชื้น CBR และ ϕ_p ในพจน์ของอัตราส่วนการแทนที่ RCA ผู้ประกอบการงานถนนสามารถประยุกต์ใช้สมการดังกล่าวในการเลือกวัสดุผสมจากแหล่งต่างๆ เพื่อใช้เป็นวัสดุการทาง ซึ่งเป็นประโยชน์ในทางด้านวิศวกรรม เศรษฐกิจ และสิ่งแวดล้อม

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SEREYROATH CHEA : ASSESSMENT OF PHYSICAL AND GEOTECHNICAL PROPERTIES OF RECYCLED CONCRETE AGGREGATE AND CRUSHED ROCK BLENDS. THESIS ADVISOR : PROF. SUKSUN HORPIBULSUK, Ph.D., 88 PP.

RECYCLED CONCRETE AGGREGATE/ GEOTECHNICAL TESTING/ PAVEMENT MATERIAL

In recent years, there has been an environmental push worldwide to continually seek new reuse applications for various waste materials. This research aims to investigate physical and geotechnical properties of Recycled Concrete Aggregate (RCA) and Crushed Rock (CR) blends for pavement applications. The particles of RCA and CR are the same and meet the specific requirement of Department of Highways, Thailand. The laboratory experiments including particle size distribution, particle density, water absorption, Los Angeles (LA) abrasion, compaction, California Bearing Ratio (CBR), and direct shear test were undertaken on various blended samples. The RCA was blended with CR at replacement ratios of 0%, 30%, 50%, 70% and 100%. The increase of RCA content results in the increase in Optimum Water Content (OWC) due to the high water absorption of mortar of RCA particles. Due to the low strength of RCA particles, LA abrasion increases with increasing RCA content. The results show that RCA-CR blends with RCA replacement ratios between 30 and 100% can be used as sub-base and base materials, where their LA abrasion varies from 17-39%, water absorption from 2.4-4.2% and CBR from 36-128%. The effect of RCA on the shear response of blended materials shows that the peak shear strength decreases as the

RCA replacement ratio increases. The tan ϕ_p varies from 0.52-1.00 for RCA replacement ratio ranging from 0% to 100%, where ϕ_p is peak friction angle. Shear strength difference between the peak state and the critical state reduce with increasing the RCA replacement. Since the initial gradation of RCA and CR are the same, the reduction in dilatancy induced shear strength is mainly caused by the crushing of RCA particles during compaction. The relationships between LA abrasion, water content, CBR and ϕ_p versus RCA replacement ratios are proposed, which are useful to geotechnical and pavement practitioners for selection of pavement materials and pavement design. The equations can also be extended to predict the blended materials with different gradation of each origin compositions. This research will enable RCA traditionally destined for landfill to be used in sustainable manner as an aggregate in pavement base/subbase, which is significant in term of engineering, economic and environmental perspectives.

School of Civil Engineering Student's Signature________________

Academic Year 2014 Advisor's Signature________________

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Sereyroath Chea

TABLE OF CONTENTS

Page

TABLE OF CONTENTS (Continued)

Page

TABLE OF CONTENTS (Continued)

Page

LIST OF TABLES

Table **Page**

LIST OF FIGURES

Figure **Page**

LIST OF FIGURES (Continued)

Figure **Page**

CHAPTER I

INTRODUCTION

1.1 Statement of problem

With urban development, the infrastructure such as highways, bridges and buildings are being constructing. Granular materials are then increasingly being used for concrete production and pavement applications. Subsequently, large amount of natural resources are consumed every day and large amount of waste materials are generated and destined for landfill.

Construction sectors generate large amount of Recycled Concrete Aggregate (RCA) from demolition concrete structures. FHWA (2004) mentioned that RCA is generally generated from old concrete pavements, bridge structures or decks, sidewalks, curbs and gutters that are removing from service. RCA is increasing globally due to rapid increase in construction and demolition activities in construction sectors.

Several countries, states, and agencies have raised concerns of availability of natural aggregate and the growth of amount of waste dispose back to environment and it leads to reuse of the construction and demolition waste materials as an alternative aggregate.

To reduce the usage of natural resources and the waste dispose to the environment, recycled materials have been increasingly used by the infrastructure sector.

Disfani et al. (2012); Tam and Tam (2007) found that the usage of recycled concrete aggregate would significantly reduce carbon footprints and environmental friendly. Arulrajah et al. (2013) extensively investigated the usage of RCA in both pavement base and subbase applications. Past studies carried out to characterize RCA for pavement application indicated that RCA can be used as subbase materials successfully (Arulrajah et al., 2012; Arulrajah et al., 2013; Gabr & Cameron, 2012; Poon & Chan, 2006). Arulrajah et al., (2013) and Dam et al. (2011) have reported that RCA exhibits low water absorption and Los Angeles abrasion value and high CBR values that meet the requirement for pavement sub-base layer.

The construction sectors regularly stabilize the marginal material with Portland cement while the manufacture process of the cement causes greenhouse effect and global warming. In this research, replacement method is used to improve the properties of RCA; RCA might be blended with high quality materials. Crushed Rock (CR) could be considered as a high quality material.

This research aims to study the properties of RCA-CR blends for pavement base applications. Both gradation of RCA and CR were adjusted to be the same and consistent with the requirement by the Department of Highways and Department of Rural Roads, Thailand. The effect of RCA, as replacement material, on the physical and geotechnical properties such as water absorption, Los Angeles abrasion, CBR and shear strength are examined. 0%, 30%, 50%, 70% and 100% of RCA replacement ratio were used in this study to find out the optimum blend for pavement base and subbase materials. Predictive equations of geotechnical properties of blends at different proportions are finally proposed, which is important for pavement design and for selection of pavement materials. The equations are formulated using engineering properties of RCA and CR as references. The outcome of this research is fundamental of suitable green pavement materials selection.

1.2 Research Objective

This research aims to assess the physical and geotechnical properties of RCA and CR blends as pavement base/subbase material. The objectives of this study are:

- ❖ To study the physical and geotechnical properties of RCA-CR blends having same gradation.
- ❖ To ascertain the physical and geotechnical properties of RCA-CR blends as pavement base/subbase material according to requirement of Department of Highways and Department of Rural Roads, Thailand.
- ❖ To propose predictive equations of geotechnical properties of the RCA-CR blends.

1.3 Structure of presentation

This thesis consists of five chapters and the outline is presented as follows:

Chapter II describes the literature review of previous researchers on Construction and demolition materials.

Chapter III presents the methodologies and laboratory test to investigate the physical and geotechnical properties of RCA-CR blends.

Chapter IV reported the physical and engineering properties of RCA-CR blends and the analysis of the test result. Finally yet importantly, the conclusion and recommendation will be summarized in chapter V.

CHAPTER II

LITTERATURE REVIEW

2.1 General

Since 1990s, several researchers have studied the usage of recycled materials as substitute materials for geotechnical structure. In term of engineering, economic and environmental reasons, C&D materials have been used in infrastructure sector (Dosho, 2007; FHWA, 2004). Due to the limitation of natural resources and high cost of waste disposal, recycled materials have been studied and have been used in Europe. Even though Asia is rich in natural resources, the use of by-product materials has been also used. It can reduce the demand of natural aggregate, reduce carbon footprint and sustain the usage of virginal aggregate. Furthermore, quarry blasting process, crushing, transport, and stocking consumes a lot of energy and seriously ruin the environment. Then we need to break the way curb using virginal material and reuse by product materials.

The viability of recycled material in construction industry would benefit in two ways. First, the extraction of natural aggregate and waste disposal would reduce. Second, the cost of construction might be cheaper.

To increase and enhance the utilization of recycled materials, the extensive study has widely investigated the possibility of usage of waste materials for various applications. This research investigated the physical and geotechnical properties of

Recycled Concrete Aggregate (RCA) and crushed rock (CR) blends at different replacement ratios for pavement base/subbase applications.

2.2 Waste materials

Waste materials are generated from various sections such as industrial, household, construction, agriculture (Kumar et al., 2012). C&D materials are a waste material from process of construction, renovation or demolition of structure, which include building of all types of both residential and nonresidential, road and bridges. Ali (2012) stated that the demolition waste materials are the materials those arise from demolition activities and are generally homogenous by nature. Homogeneity increases the possibility to reuse or recycle waste materials. Construction debris is composed of brick, wood, steel, ceramic, plastic, paper old asphalt and glass.

To effectively study, the waste material is classified in various types and must be zero deleterious material. Their main components are as follows (Portas, 2004):

- Crushed Brick (CR)
- Concrete Aggregate
- Reclaimed Asphalt Pavement (RAP)

It is possible to find other C&D materials, but the percentage is low compared with these main components mentioned above. In general, it is not easy to evaluate C&D material composition as it varies greatly with location, level of industrialization and construction techniques all over the countries (Portas, 2004).

2.3 Recycled Materials in different countries

Aggregate consumption had increased to 202 million tons by 1986 in England and Wale and was expected to rise to 226 million tons by 1995 and 245 million tons by 2005. An advisory committee on aggregate considered and concluded on future supply of aggregate for the construction industry the aggregate should be an adequate and steady supply of materials to meet needs of construction industry at minimum financial and social cost (O'Mahony, 1990).

In Japan, an investigation conducted in 2002 by the Ministry of Land, Infrastructure and Transport. The amount of construction wastes produced in Japan approximately 83 million tons per year. Concrete waste accounts for approximately 35 million tons per year. Although the recycling rate of concrete waste has reached 98%, most of it is used for roadbed gravel (Dosho, 2007).

FHWA (2004) reported that two billion tons of aggregate are produced each year in the United States. Production is expected to increase to more than 2.5 billion tons per year by the year 2020. On the other hand, Lim et al. (2003) indicated that 100million tons of crushed concrete are generated annually in the United State. Texas Department of Transportation has presented the use of all size particle of crushed concrete as a base layer material with cement treatment.

ECCE (2009) mentioned that Construction and Demolition (C&D) wastes amount to more than 450 million tons per year in The EU. However, these figures should be placed in their proper perspective. Most of C&D materials are todays recycled or reused principally in the form of embankment. A significant proportion could potentially be used as a substitute for newly quarried aggregates in certain lower grade application.

Ali (2012) stated that in Victoria, Australia the total amount of the recovered waste material was recorded as 6.56 million tons during the financial year 2008-2009 and around 64% of the solid waste were recycled over that period. Among C&D materials, concrete was the major component representing 55% (by weight) of the total followed by rock/excavation stone (21%), brick/brick rubble (8%), soil/sand (5%), asphalt (7%), mixed C&D waste (3%) and plasterboard (1%).

Sarkar (2012) reported that the solid waste generation in India was about 48 million tons per annum and more than 25% of this from the construction industry which consists of about 7-8 million tons of concrete and brick waste. The waste quantities are estimated to reach to the level of at least 65 million by 2010. The concrete industry uses approximately 10 billion tons of sand and natural rock worldwide, and more than 10 billion tons of construction and demolition waste are produced every year.

Bansal and Singh (2014) denoted that in 2009, 42.1 million tons of demolished concrete was generated, which was 63% of all C&D wastes and effective recycling rate was 36% in Korea. The usage of recycled materials was for road sub-base construction or equivalent, concrete blocks and recycled aggregate for concrete.

2.4 Advantage and Limitation

Dam et al. (2011) indicated that recycled crushed concrete has been used in application ranging from placement in various paving layers (surface, base, sub-base) and as fill and embankment materials. In fact, the use of recycled materials is directly considered and earns credit in several infrastructure sustainability-rating systems that have recently been developed such as Green road and the sustainable highways self-evaluation tool.

FHWA (2004) presented that transportation agencies' experiences and research studies have shown that Recycled Concrete Aggregate (RCA), under specific conditions, had the potential to produce strong, durable materials suitable for use in the highway infrastructure. The coarse aggregate portion of RCA has no significant adverse effects on desirable mixture proportion or workability. Recycled fine, when used, were generally limited to about 30% of the fine-aggregate portion of the mixture.

At the same time, RCA had number of unique characteristic and properties that must be considered during the design and construction process. Typically, RCA exhibits the following characteristics when compared to natural aggregates (Dam et., 2011):

- ❖ Lower specific gravity, which decreases with increasing amount of reclaimed mortar
- ❖ Higher absorption, which increases with increasing amount of reclaimed mortar
- ❖ Greater angularity
- ❖ Increase abrasion loss, which increases with increasing amount of reclaimed mortar

RCA can be broadly used in many of the same applications as natural aggregate including the following:

- ❖ Unbound (granular) base and back fill (including both dense-grade and free-draining)

- ❖ Cement-stabilized base (permeable and dense-graded)
- ❖ Asphalt-stabilized base (permeable and dense-graded)
- ❖ Concrete mixture (surface layers, lean concrete base)
- ❖ Asphalt pavement mixtures
- ❖ Granular fill
- ❖ Miscellaneous applications such as soil stabilization, pipe bedding, landscape materials, and railroad ballast (Dam et al., 2011).

EPA (2009) mentioned that C&D materials were composed of chemical and physical properties that made them valuable resources when recycled or beneficially reused but they are often disposed of as waste. The use of recycled material would benefit in different ways such as:

- ➢ Environmental Benefits

Since many C&D materials are used to replace non-renewable virgin materials that must be mined and processed, using industrials materials conserve natural resources and reduces the energy use and pollution associated with these activates (Dosho, 2007; Kumar et al., 2012). Road and other structures made with industrial materials can be more durable while maintaining and replacing road less frequently is good for the environment because it conserves natural resources and energy.

- ➢ Economic Benefits

C&D materials are often less expensive than virgin materials they replace, and recycling or reusing materials onsite can reduce materials hauling and disposal costs.

Putting C&D materials to use in infrastructure projects also reduces the cost of waste disposal, the need for new or expanded landfills, saving valuable landfill capacity (FHWA, 2004; Dosho, 2007; Mack et al., 1993).

- Performance Benefits

C&D materials offer significant performance enhancement benefits such as the angularity of RCA that helps increase structural strength in the base, resulting in improved load carrying capacity (FHWA, 2004). The residual cementitious material in recycled concrete provides bonding of the base material, over and above that provided with the fines in virgin aggregate. This provides a very good construction base for new pavements, as well as handles construction equipment on the aggregate base, giving the contractor help in construction of the highway projects.

- Green Design

C&D materials are encouraged for highway construction and renovation activities that have a reduced impact on the environment. In fact, the use of recycled materials is directly considered and earns credit in several infrastructure sustainability rating systems that have recently been developed, such as Green-road and the Sustainable Highways Self-Evaluation Tool (Dam et al., 2011).

2.5 Experiences

- Texas

Initially, there was a general perception among the engineers that RCA was a waste product and thus a substandard material. However, over time that perception in Texas Department of Transportation (TxDOT) has changed due to education and test section finding. The placement of RCA base material has provided some hurdles in grading and compacting. Compaction of the RCA base should be in a saturated state to aid in the migration of fines throughout the mix. Overall, the performance of RCA as base materials has been excellent; the material even tends to knit together and has a higher load bearing capacity due to the re-cementing action

- Virginia

RCA is a viable material and there are written standard specification for its use in highway construction. Virginia Department of Transportation (VDOT) has provided construction recommendations for compacting RCA when it is used in base and sub-base. These recommendations include compacting the RCA in a saturated state to aid in the migration of fines throughout the mix. Compaction of RCA should be performed with steel wheel rollers, because of minor amount of steel are present in the materials and may cause problems when using rubber-tired equipment.

- Michigan

Statewide use of recycled concrete aggregate (RCA) is permitted by the standard specifications of construction, 2003. It allows the use of RCA as coarse aggregate in Portland cement concrete for curb and gutter, sidewalk, concrete barriers, driveways, temporary pavement, interchange ramps and shoulders. RCA is also allowed permitted to be used as coarse aggregate in hot mix asphalt and as dense-grade aggregate for base course, surface course, shoulders, approaches and patching.

Since the RCA is composed of coarse and fine particles, Table 2.1 provides a summary of allowable use of RCA in fill embankment, subbase, base, asphalt pavement materials and concrete base on the 2012 MDOT Standard Specification for Construction (Dam et al., 2011).

Table 2.1 Summary of allowable use of RCA (Dam et al., 2011)

Type of RCA	Fill/Subbase	Dense-Graded Aggregate	Open-Graded Aggregates	HMA	PCC
Coarse	Yes	Yes	Yes	Yes	Yes
Fine	Yes	Yes	Yes	No	No

- Minnesota

The Minnesota Department of Transportation (Mn/DOT) has permitted the use of RCA in construction. The specification establishes that RCA can be used as coarse aggregate in Portland cement concrete (PCC) as aggregate for surface and base course and granular material.

Mn/DOT and other industries have overcome some barriers of using recycled aggregate.

- Observations suggest that RCA when used in the base and sub-base material performs better than virgin aggregate. Research is underway to determine if the observed increase in base strength can be validated in a laboratory performance evaluation for RCA used in aggregate base and sub-base. Rubblization, crack & seat and un-bounded concrete overlays have been used as reconstruction strategies. All these processes have shown to provide good performance.

❖ Substitution of RCA for virgin aggregate can provide saving in the final cost of the project. It is a common practice in Minnesota to crush the material on site. This lower the transportation costs and has less effect on traffic.

❖ Use of RCA preserves natural aggregate resource.

Recommendations provided by Mn/DOT for using RCA in state highways are:

- ❖ Washing of RCA is required if used in Portland Cement Concrete (PCC) pavements in order to eliminate excess fines.
- ❖ Quality requirement for new aggregate does not specifically apply to RCA when the pavement comes from a known source
- ❖ In presence of drainage layers and / or perforated drainage pipe, a blend of RCA with new aggregate may be used as subgrade when at least 95% of the RCA is retained on the 4.75mm sieve.
- ❖ RCA maybe used up to 100% in construction of the filter/ separation layer under a permeable aggregate base drainage layer in accordance with the applicable drainage specification.

➢ California

Most of the concrete pavement, removed from existing highways and streets in California, is processed and reused as aggregate base throughout the state. The California Department of Transportation's specification for aggregate base allows any mixture of recycled concrete aggregate and recycled asphalt pavement. This provided the contractor's with freedom to choose the base material providing the most economical base available.

The City of San Francisco is developing a specification allowing RCA in all non-structural concrete applications. This permits its use in curbs, gutters and sidewalks. The California Department of Transportation is also working on a similar specification for their use.

- Japan

Industrial Standards define three classes of concrete depending upon the properties of recycled coarse and fine aggregate:

- Class H: Having density of coarse and fine aggregates more than 2500kg/cum. Water absorption is lesser than 3% for coarse aggregates and lesser than 3.5% for fine aggregates. Such products are put into use without any limitation for concrete strength up to 45MPa.

- Class M: Having density of coarse more than 2300 Kg/cum and of Fine aggregate more than 2200 Kg/cum. Water absorption is lesser than 5% for coarse aggregates and lesser than 7% for fine aggregates. Such products are allowed to be used where members are not subjected to drying or freezing and thaw action like piles, underground beams and concrete filled in steel tubes.

- Class L: Having water absorption lesser than 7% for coarse aggregate and lesser than 13% for fine aggregate. Such productions are used only as backfill concrete, blinding concrete and leveling concrete.

2.6 Existing Research

To understand the reuse potential of C&D waste and existing practices in implementation and enforcement for achieving, the aim with an ultimate motive of engineering, environmental and economic perspectives. Since the reuse of C&D waste is always more advantageous, it is essential to extensively study, review and suitably modified in order to establish of effective strategies and enactment of regulations of using C&D materials and to promote the use of recycled products. RCA has been investigated several decades ago for concrete and pavement applications.

Concrete is primarily a composition of cement, coarse aggregates, fine aggregate and water, further processed by addition of industrial products or by products for enhancing the properties. Engineers are mainly dependent on nature for obtaining the coarse and fine aggregates as well as water for the chemical reaction with cement. One of the alternative sources of coarse aggregates is recycled concrete aggregate (RCA), which is obtained from the processed Construction & Demolition waste.

At early age, RCA had low compressive strengths whereas 28-day concrete had achieved the strengths of corresponding controls at more consistent rates. The difference in compressive strength of recycled aggregate and natural aggregate was insignificant effect on the geotechnical properties of blends. The better particle interlocking in recycled concrete and the cleaner of RCA from attached mortar, the higher strength of specimens. To gain the same aspect as natural aggregate, some efforts are required to improve RCA properties (O'Mahony, 1990).

FHWA (2004) found that RCA is a valuable resource and by proper engineering it can be used for Portland Cement Concrete pavement, aggregate base, miscellaneous.

Some of the best aggregates used for highway, bridge, and building construction are already in use in highways and bridges, effective recycling is a means to re-use these materials. Recycled fines, when used, are generally limited to about 30% of the fine aggregate portion of the mixture.

Snyder et al. (1994) compared some of the typical properties associated with RCA and natural aggregate materials as listed in Table 2.2. RCA is very angular as a result of the crushing process.

Table 2.2 Comparison of typical natural aggregate and RCA properties (Snyder et al., 1994)

Property	Natural Aggregate	RCA
Particle Shape and Texture	Well rounded, smooth (gravels) to angular and rough (crushed stone)	Angular with rough surface
Absorption Capacity	0.8 - 3.7 %	3.7 – 8.7 %
Specific Gravity	2.4 – 2.9 %	2.1 – 2.4
L.A Abrasion	15 - 30 %	20 – 45 %
Sodium Sulfate Soundness	7 – 21 %	18 – 59 %
Magnesium Sulfate Soundness	4 – 7 %	1 – 9 %
Chloride Content	0 – 2 lb/yd^3 (0 – 1.2 kg/m^3)	1 – 12 lb/yd^3 (0.6 – 7.1 kg/m^3)

Primary reasons for other differences in the properties lie in the fact that RCA is composed of both the original natural aggregate and a reclaimed mortar fraction, the combination of which results in a higher absorption, a lower specific gravity, and potential for decreased abrasion resistance, which could not reach the high requirement strength of designed materials.

Usually the desired materials are not available locally in sufficient quantities. Foreign materials need to be brought from far off place, which increase the transportation cost. There would be economical benefit of using locally available materials. The selection of materials for construction plays a prominent role in the pavement construction and its performance. Somehow, the quality of locally available aggregate or borrowed aggregate would not meet the standard specification. Locally aggregate or borrowed aggregate would be modified by using following methods, which result in lesser thickness of pavement layer and better pavement performance.

- Cement or lime stabilization
- Replacement method

Several researchers, designers, contractors have used both methods for various investigations and engineering applications. To emphasis on environmental issue, cement or lime treatment is not an environmental friendly method. Since the cement or lime production generates the carbon footprint to the atmosphere. Thus, replacement method is an alternative one for strength improvement.

Dosho (2007) studied RCA by using replacement method for structural concrete and/or precast concrete productions. It was reported that, RCA could acquire sufficient quality as structural concrete through material design.

Similarly, Surya et al. (2013) reported the properties of recycled aggregate and recycled aggregate concrete, to verify their utilization in civil infrastructure. Five different concrete mixes were produced; it was observed that there was no significant variation in compressive strength, split tensile strength and flexural strength of concrete while the modulus of elasticity and resistivity decreased and water absorption increase with increased in percentage of recycled aggregates.

Arulrajah et al. (2013) examined the geotechnical and geoenvironmental properties of five predominant types of C&D materials for pavement application. The C&D materials tests were recycled concrete aggregate (RCA), crushed brick (CB), waste rock (WR), reclaimed asphalt pavement (RAP). A detailed laboratory investigation was undertaken to characterize of C&D materials in term of their basic properties, shear strength parameter, resilient modulus, and permanent deformation characteristics. Table 2.3 indicates the existence of high quality aggregates in the recycled C&D materials, which contributes to higher density for the coarse aggregates. LA abrasion test indicated that RCA, WR and FRG were more durable in abrasion than CB and RAP. RCA, CB and WR met the CBR requirements for usage as subbase materials.

In addition, Kavak et al. (2011) recommended that in the earth fill works, it was important to find a materials with good compaction characteristics that provides a permanent operational solution. RLT results indicated that RCA, CB and WR performed satisfactorily at 98% MDD and at a target moisture content of 70% of the OMC. The performance of RCA, CB and WR were found to be affected by increasing the target moisture contents and the density level, particularly for CB which failed at the higher target moisture contents of 80%-90%. RCA, WR were found to have much smaller permanent strain and much higher modulus than natural granular subbase, which indicated their performance as superior or equivalent to typical quarry materials.

Table 2.3 Geotechnical Properties of Recycled C&D materials (Aruraljah et al., 2013)

Geotechnical Parameters	RCA	CB	WR	RAP	FRG	Quarry
D_{10} (mm)	0.24	0.18	0.075	0.24	0.16	-
D_{30} (mm)	1.3	1.7	1.5	1.9	0.45	-
D_{50} (mm)	5.0	5.6	3.9	4.5	0.85	-
D_{60} (mm)	7.5	8.0	5.6	5.9	1.2	-
C_u	31.2	44.4	74.7	25.6	7.5	-
C_c	0.9	2.0	5.4	2.5	1.5	-
Gravel content (%)	50.7	53.6	44.7	48.0	0.0	-
Sand content (%)	45.7	39.8	45.1	46.0	94.6	-
Fine content (%)	3.6	6.6	10.2	6.0	5.4	<10
USCS classification	GW	GW	SW	GW	SW	-
Particle density-coarse (kN/m^3)	27.1	26.2	28.1	23.5	24.4	>19.62
Particle density-fine (kN/m^3)	26.0	25.8	28.0	23.4	24.3	>19.62
Water absorption-coarse (%)	4.7	6.2	3.3	2.2	1.0	<10
Water absorption-fine (%)	9.8	6.9	4.7	2.4	1.8	<10
MDD (kN/m^3)-modified	19.13	19.73	21.71	19.98	17.40	>17.5
OMC (%)- modified	11.0	11.25	9.25	8.0	10.5	8-15
Organic content (%)	2.3	2.5	1.0	5.1	1.3	<5
pH	11.5	9.1	10.9	7.6	9.9	7-12
Hydraulic conductivity (m/s)	$3.3.10^{-8}$	$4.5.10^{-9}$	$2.7.10^{-7}$	$3.5.10^{-7}$	$1.7.10^{-5}$	$>1.10^{-9}$
Flakiness index	11	14	19	23	-	<35
LA abrasion loss (%)	28	36	21	42	25	<40
CBR (%)	118-160	123-138	121-204	30-35	42-46	>80
Triaxial test (C&D): c (kPa)	44	41	45	53	0	>35
Triaxial test (C&D): ϕ (degree)	49	48	51	37	37	>35
Resilient modulus: 90% OMC	239-357	301-319	121-218	-	-	125-300
Resilient modulus: 80% OMC	487-729	303-361	202-274	-	-	150-300
Resilient modulus: 70% OMC	575-769	280-519	127-233	-	-	175-400

Kumar et al. (2012) investigated the use of recycled aggregate from building waste as base course and sub-base course. Aggregate was found to be relative soft compared with conventional aggregate and can be used as sub-base material but not in base course and wearing course. Water absorption of RCA was found to be high as compared with conventional aggregate. Arulrajah et al. (2012) also reported that the RCA tested satisfies the criteria for use in pavement subbase applications only. The degree of breakdown occurring in the RCA in on the limit of what would be acceptable for this material. Figure 2.1 shows the gradation limits of all RCA samples, “before” and “after” compaction, were compared to and found to be within the local state road authority specified upper and lower bounds for usage of aggregate as a pavement subbase application.

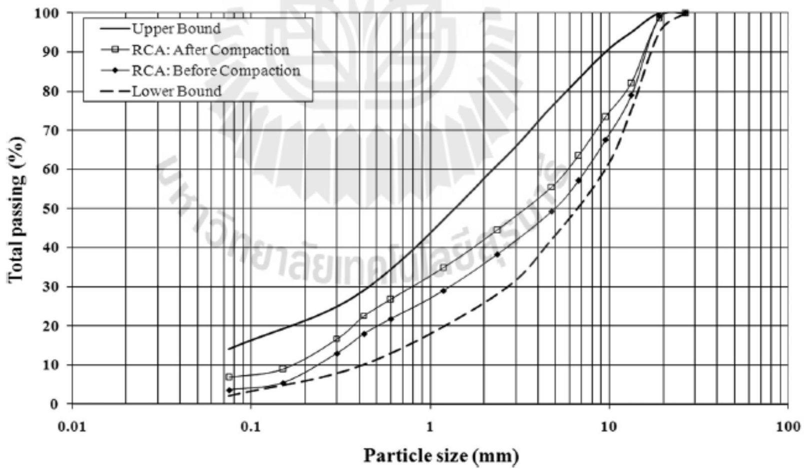

Figure 2.1 Particle size distribution of RCA before and after compaction (Arulrajah, et al., 2012)

The Los Angeles abrasion test results were found to be below the maximum limit adopted by the local state road authority, indicating that the RCA is durable. CBR value obtained was found to satisfy the local state road authority requirement for subbase materials.

Leek and Siripun (2010) detailed the laboratory characterization and performance of RCA material from Western Australia. Their report summarized the results of most of the laboratory tests of interest and presented file trial results over two year for three RCA materials and two virgin aggregates. The authors found that RCA was suitable for high stress applications and should be considered for use as a premium base course product. However, concerns raise about the rehydration of the cement within the RCA materials in the long-term and so with time, an excessively stiff material might be produced which may suffer fatigue.

The suitability of crushed concrete or recycled concrete aggregate material (nominal size 20mm) and quartzite blends have been evaluated for use as pavement material for unbound base courses (Gabr & Cameron, 2012). Laboratory test result showed that the resilient modulus of RCA products was greater than that of a local quartzite used as virgin aggregate for road base. The permanent strain rate was acceptable for RCA products, however, the virginal aggregate materials prepared at 90 and 80% OMC did not achieve the maximum requirement. Shrinkage of RCA effectively ceased after 84 days of drying. The self-cementing nature of RCA was confirmed with the gain in unconfined compressive strength with time.

Similarly, Nataatmadja and Tan (2001) evaluated the resilient modulus of four RCAs. The materials were produced by crushing concrete beams with a compressive strength ranging from 15 to 75 MPa. Resilient modulus was observed to increase with an increase in the compressive strength of the source concrete. The study concluded that that resilient modulus of RCA was comparable, if not better, than that of typical virgin road aggregate. Therefore, RCA products were believed to have suitable application as either a subbase or base course, provided appropriate product quality standards were met.

Arulrajah et al. (2012) focused on the characterization of recycled crushed brick when blended with recycled concrete aggregate for pavement application. The grading limits of all blends “before and after” compaction were also within typical state road authority specified upper and lower limits for pavement sub base.

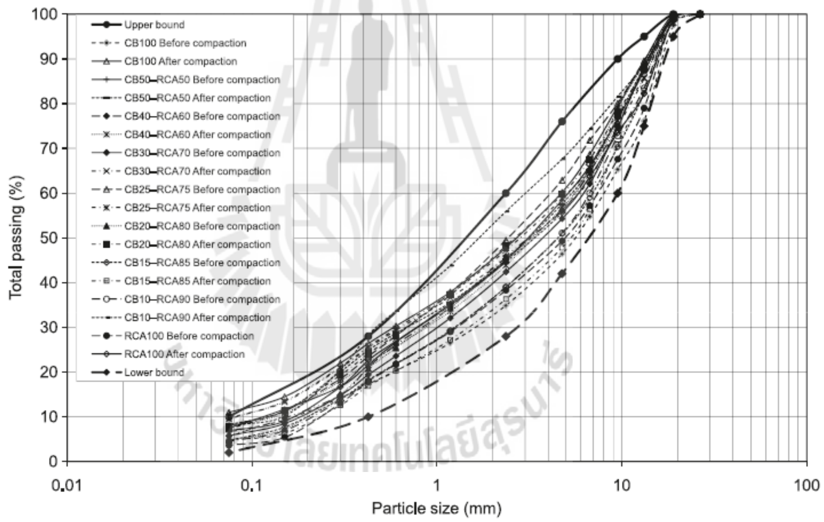

Figure 2.2 Particle size distribution of CB-RCA blends before and after compaction (Arulrajah et al., 2012)

Arulrajah, Ali, et al. (2014) evaluated the use of recycled glass blends as unbound pavement base/subbase materials. Recycled aggregates were used by means of experimental and field-testing were Fine Recycled Glass (FRG), Recycled Concrete Aggregate (RCA), and Waste Rock (WR) in blends in pavement base applications.

The geotechnical performance and properties of FRG additive in blends with RCA and WR in pavement base was assed.

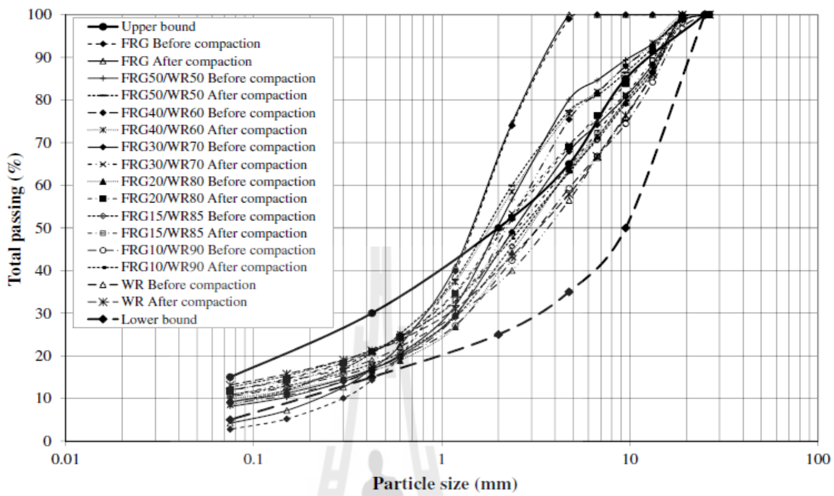

Figure 2.3 Particle sizes distribution of various FRG/RCA blends (Arulrajah et al., 2014)

From field and laboratory test result of various specimens from different grain size distribution curve, maximum 20% of FRG blends are suitable for pavement subbase application.

Conversely, Kavak et al. (2011) denoted that different gradation materials provided different properties filling materials. In this case, the soil's bearing capacity and deformation under loads changes. Thus, it is important to predetermine the effect of these changes in soil parameters on filling behavior. To study the effect of replacement materials, the specimens should be prepared from same gradation, which will be performed in this study.

The base layer is unbound layer that is subjected to vertical compression stress induced by traffic and distribute the stress to sub-base layer. These two layers are unacceptable large deformation (Croney & Croney, 1991). Thus, base layer must be constructed by high quality material to support vertical load. Since RCA met requirement of subbase only, the RCA's strength should be improved to be stiffer for base pavement application.

2.7 Summary of Previous Researchers

Previous studies indicated that due to water absorption, Los Angeles abrasion, California Bearing Ratio (CBR) and resilient modulus of maximum size of 20 mm of RCA in geotechnical applications could be used in pavement sub-base successfully. Age and historical strength of concrete would influence the geotechnical properties of RCA. Since the early age of concrete blocks provides low strength whereas 28-day concrete had achieved the strength of corresponding control at more consistent rate. The higher historical compressive strength of concrete, the better geotechnical properties. Due to low stiffness of RCA particles, some effort is required to improve RCA properties. Several searchers have improved RCA's strength by cement treatment or replacement with other good quality materials such as crushed rock (CR). Cement treatment is not environmental friendly method. As such, replacement method was used in this investigation.

This research aims to improve physical and geotechnical properties of RCA by blending with CR for base course layer. RCA was obtained by crushing 28-day cube concrete. The means 28-day strength was 28.5MPa with deviator stress of 11.9MPa. Both RCA and CR were prepared to have the same gradation curve and consistent with the requirement by the Department of Highways and Department of Rural Roads for pavement application.

CHAPTER III

SAMPLING AND LABORATORY TESTING METHODOLOGY

3.1 Introduction

The usage of recycled waste materials in sustainable manner in the civil engineering application supports zero-waste directives currently implemented in many developed and developing countries. As such, there has been available research on Recycled Concrete Aggregate (RCA) in pavement application as unbound base/subbase materials (Poon & Chan, 2006; Gabr & Cameron, 2012; Aruraljah et al., 2012; Azam & Cameron, 2013). It was revealed that some geotechnical properties of RCA were not suitable for base layer and RCA need to be improved either by chemical stabilization or replacement method with other good quality materials such as Crushed Rock (CR). The construction sectors regularly use Portland cement for stabilization in which the production of the cement causes greenhouse effects and global warming.

Therefore, this research improve the geotechnical properties of RCA by blending with CR. The geotechnical laboratory tests were undertaken on CR-RCA blends with RCA replacement ratios of 100%, 70%, 50%, 30% and 0%. To avoid the effect of different gradation of CR and RCA on the interpretation of the test results, the RCA and CR were prepared with the same gradation in this study. The evaluation of the physical and engineering properties of RCA-CR blends such as water absorption, Los Angeles abrasion, CBR, shear strength parameters, are significant further to understand these alternative materials. There is available research on properties responses of recycled Construction and Demolition (C&D) materials for various purpose (Arulrajah et al., 2012; Arulrajah et al., 2014; Disfani, et al., 2011; Mckelvey et al., 2002; Rahman et al., 2014).

This research aims to investigate physical and geotechnical properties of RCA-CR blends in different RCA replacement ratio. The possible mechanism controlling the strength was also presented. The outcome of this study would be a fundamental understanding and design of various recycled materials in geotechnical applications.

3.2 Laboratory Investigation

3.2.1 Materials

Concrete blocks as shown in Figure 3.1 were collected from Bureau of Rural Road 5, Department of Rural Road, Nakhorn Ratchasima, Thailand.

Figure 3.1 Concrete Blocks

The mean 28 day-cube strength of the original concrete is 28.5 MPa with standard deviation of 11.9 MPa.

Concrete blocks were manually crushed by a hammer into various particle sizes as illustrated in Figure 3.2. Subsequently, RCA was categorized into different sizes of aggregates by sieving.

Figure 3.2 Recycled Aggregate Concrete

Figure 3.3 Crushed Rock

Crushed Rock (CR) (Figure 3.3) was collected from a quarry in Chok-Chai district, Nahkon Ratchasima, Thailand. It was sourced from a basalt rock with a maximum particle size of 20 mm and was classified as type C aggregate (ASTM D1241, 2007). Since Los Angeles (LA) abrasion value was less than 35% and the grain size distribution curve of CR, as shown in Figure 3.4, was consistent with the requirement of Department of Highways and Department Rural Road, CR is considered as good quality materials. Then, RCA's gradation was adjusted to be the same.

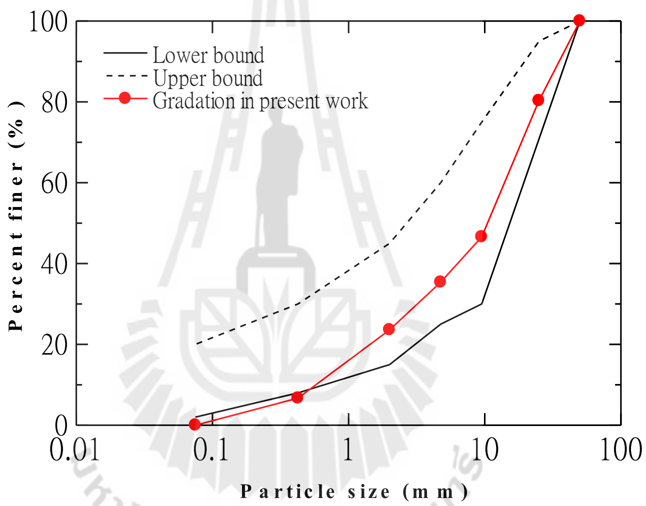

Figure 3.4 Particles size distribution curve

Again, since the properties of RCA could not meet the pavement base's requirement, RCA's properties needs to be improved. To emphasis on environmental issue, replacement ratio was be used to investigate. To find out the optimum blends of RCA content which meet the requirement for base pavement. 0%, 30%, 50%, 70%, and 100% of RCA content were used in laboratory study. Several laboratory experiments were conducted:

- Physical Properties
  - Particle Size Distribution
  - Particle Density Test
  - Water Absorption Test
  - Los Angeles Abrasion Test (LA)
  - Modified Compaction Test
- Geotechnical Properties
  - California Bearing Ratio Test (CBR)
  - Direct Shear Test (DS)

3.2.2 Experiments

3.2.2.1 Particle Sizes Distribution Test

Atkinson (2007) mentioned that strength and stiffness of a soil depend principally on the nature of the grains and the state of the soil. Scheme of classification separates groups of soils with markedly different behavior. For civil engineering purpose, soil classifications should be based mainly on mechanical behavior. Das (2000) showed that there are four different soil classification systems recently:

- Massachusetts Institute of Technology (MIT)
- U.S Department of Agriculture (USDA)
- American Association of State of Highway and Transportation Officials
- Unified Soil Classification System (USCS)

USCS has been widely used and accepted by many stakeholders, the American Society for Testing and Materials (ASTM) has accepted it.

The USCS is based on the recognition of the type and predominance of the constituents considering grain-size, gradation, plasticity and compressibility. It classifies soil into four major categories:

- Coarse-grained
- Fine-grained
- Organic soils
- Peat

ASTM D2487 (2011) defined 4.75mm or sieve No.4 as a borderline between sand and gravel particle. Particle retained on sieve No. 200 (75 µm) U.S standard sieve is classified as silt and soil pass a No. 200 sieve is clay.

In order to classify the tested sample, particle size distribution and sieve analysis were a means that the predominant particles indicate type of soil namely gravel, sand, silt or clay. Two methods could be used to determine size of the particles present in a sample. These are sieve analysis and hydrometer procedures. Through a series of sieve of standard aperture opening, sieving analysis was used with coarse material. However, for fine particle, which is smaller than 75µm, the hydrometer analysis was performed.

Sieve Analysis consists of two different methods. Dry and Wet sieve analysis (O'Mahony, 1990).

- Dry Sieve Method

A set of square opening sieve have progressively smaller opening. Materials are separated into fraction. For coarse aggregate, it is effectively separated by using inclined screens vibrating at low frequencies and small amplitudes, whereas the high frequency of vibrations and small amplitudes is used for fine materials. This main disadvantage of dry sieve method is too much dust is generated during shaking.

❖ Wet Sieve Method

It is used for low density and contaminated material. The demolition debris could be removed by using an aquamator. This method of separation is conducted by mixing materials with the water. Demolition debris such as wood and other lightweight objects, which float in water are removed. This technique is used for cohesive soils, because it may be difficult to break the lumps into different particle size. The soil is mixed with water to make a slurry and then washed through the sieves. The portions retained on sieve are collected separately and oven dried before weighting the retained mass.

For both dry and wet sieve methods, the retained mass on each sieve is generally expressed as the percentage of the total weight of soil that passed through different sieves size. In this study, particle size distribution tests were examined in accordance to (AASHTO T27/T11, 2013). Since RCA and CR were type C aggregate with maximum diameter of 20 mm, the dry sieve analysis was used.

First, concrete blocks were manually crushed into small dimension by hammer. Then, both RCA and CR were separated into different dimension by a mechanical sieve shaker as in Figure 3.5. Table 3.1 shows the standard sieves sizes that used various dimension of aggregate. The retained mass of CR on each sieve was used to plot gradation curve. Moreover, the gradation curve was used to calculate the coefficient of uniformity (C_u) and coefficient of curvature (C_c) by equations:

$$C_u = \frac{D_{60}}{D_{10}} \tag{3.1}$$

$$C_C = \frac{D_{30}^2}{D_{60} \times D_{10}} \tag{3.2}$$

where:

D_{10} : Diameter in mm corresponding to 10% passing

D_{30} : Diameter in mm corresponding to 30% passing

D_{60} : Diameter in mm corresponding to 60% passing

C_u : Coefficient of uniformity

C_c : Coefficient of curvature

Both C_u and C_c would be unity for a single-size material, while:

$C_u < 3$ indicates uniform grading

$C_u > 5$ a well-graded material.

Most well graded materials will have gradation curves that are mainly flat or slightly concave, giving values of C_c between 0.5 and 0.2.

Table 3.1 AASHTO Standard Sieve Sizes

Sieve Number	Sieve Opening (mm)
1	25
3/4	19
3/8	9.5
4	4.75
8	2
50	0.425
200	0.075

Figure 3.5 Set of Mechanical Sieves

3.2.2.2 Particle Density Test

Particle density or specific gravity is the ratio of the mass (or weight in air) of a unit volume of a material to the mass of the same volume of water at stated temperatures. Particle density or specific gravity is denoted by the symbol (G_S), and its values are dimensionless (AASHTO T85-91, 2004).

In this research, the specific gravity was performed for coarse material retained on 4.75mm sieve. The amount of 5kg $\pm$ 0.1 of sample (Table 3.2) was prepared by sieving the materials over 19 mm sieve and retaining on 4.75 mm sieve. The dust and surface coating on the particle was removed by washing, and then the material was immersed under water about 24 hours. Next, the material was transferred into a container and immersed in a water tank below the balance as shown in Figure 3.6. The weight of the container was recorded.

Both the particle density and water absorption were determined; water on the surface of sample was dried by using cloths. It was dried until all the visible film of water has been removed. The weight of the surface dry materials was recorded. Afterward, the samples were oven dried at 110^{O}C for 24 hours and the mass of oven dried samples was recorded.

The particle density of the coarse aggregate was determine as follows:

$$G_S = \frac{A}{B-C} \tag{3.3}$$

where

A : mass of oven-dry tested sample in air (g)

B : mass of saturated-surface-dry test sample in air (g)

C : mass of saturated tested sample in water (g)

Table 3.2 Mass of Sample

Sieve Number	Mass of Tested Sample (Kg)
¾	2.5 ± 0.05
3/8	2.5 ± 0.05
Total Mass	5.0 ± 0.10

Figure 3.6 Specific Gravity Apparatus

3.2.2.3 Water Absorption Test

Water absorption is the increase in the mass of aggregate due to water in the pore of the material, but not including water adhering to the outside of the particle. It is expressed as a percentage of the dry mass. The aggregate is considered dry when it has been maintained at a temperature of 110°C ± 5°C for 24h to remove all uncombined water.

The water absorption test was performed in compliance with (AASHTO T85-91, 2004). Similarly, the aggregate was immersed under water for 24 hours. Then, water on the surface of aggregate was cleaned by cloth and weight in air as shown in Figure 3.7. Finally, the aggregate was oven dried for 24h at temperature of 110°C.

Figure 3.7 Water Absorption Test

Water absorption of coarse aggregate was calculated by the following equation:

$$W_{absor} = \frac{m_{sat} - m_{dry}}{m_{dry}} \times 100 \tag{3.1}$$

where m_{dry} : dry mass of aggregate (g)

m_{sat} : saturated mass of aggregate (g)

W_{absor} : water absorption of aggregate (%)

3.2.2.4 Los Angeles Abrasion

The Los Angeles test has been widely used as an indicator for quality and strength of the various sources of aggregate. It is a measure of degradation of aggregate of standard grading. In this research, the Los Angeles test was tested in accordance with ASTM C131 (2006).

Figure 3.8 Los Angeles Abrasion Machine and Steel Balls

This test is a measure of degradation of aggregate of standard grading resulting from a combination of action including abrasion, impact, and grinding in a rotating drum with 11 steel balls, as illustrated in Figure 3.8. As the drum rotates, a shelf plate picks up the sample and the steel spheres, carry them around until they are dropped to the opposite side of the drum, creating an impact crushing effect. The contents then roll within the drum with an abrading and grinding action until the shelf plate picks up the sample and steel spheres, and the cycle is repeated. After 15 minutes of revolution, the contents are removed from the drum and the aggregate portion is sieved to measure the degradation as percent loss.

The sample was oven dried at 105^{O}C for 24 hours before test. The mass of samples was prepared as stated in Table 3.2. The test began once the oven dried sample was cooled down about 1 hour. Then the test sample and the steel balls were placed in the Los Angeles testing machine and the machine was rotated at a speed of 30 to 33 rounds per minute for 500 revolutions. After the prescribed number of revolutions, the material was discharged from the machine and the sample underwent a preliminary separation on a sieve coarser than the 1.70 mm (No.12). Both coarse and fine aggregates after 500 revolutions were washed by water using sieve No12. Next, the retained aggregate on sieve No.12 was oven dried at 105^{0}C for 24 hours to determine the remained mass.

The Los Angeles abrasion loss was calculated by following equation:

$$\text{Los Angeles abrasion loss} = \frac{m_1 - m_2}{m_1} \times 100 \qquad (3.5)$$

where

m_1 : total initial mass before abrasion (g)

m_2 : retained mass on sieve No.4 after abrasion, washing, drying (g)

3.2.2.5 Modified Compaction Test

Bergado et al. (1996) addressed that the process of compaction is the process of increasing the unit weight by compressing the particle into a tighter state and to reduce air voids by static or dynamic forces. It leads to higher density and higher internal friction angle. Furthermore, compaction would lead to reduce the settlement, permeability of the structure.

Density is the essential indicator of the behavior of the material. Optimum Moisture Content (OMC) has been known as the best point of the compaction. The degree of compaction is the measurement between dry unit weight of laboratory test and field test. Adding water to the sample lubricates the particles and hence the particles move into the pore space under the compaction force.

The density of the sample is affected by two factors: moisture content and compaction energy exerted on the material. To determine the moisture content, a series of experiment were conducted under the various amount of water added to the sample under the certain compaction energy such as Standard Proctor test or Modifier Proctor test into 4 or 6 inches mold.

Figure 3.9 shows a typical compaction curve. The peak of the curve was known as the compaction characteristic where the Optimum Water Content (OMC) and Maximum Dry Density (MDD) were found.

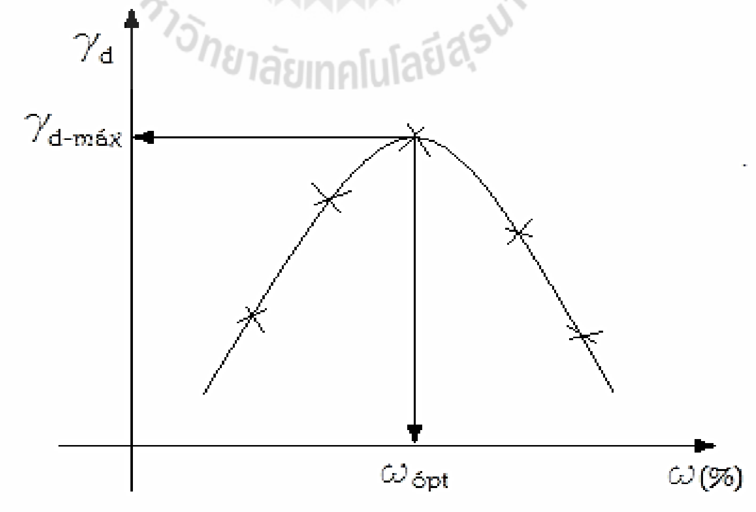

Figure 3.9 Compaction Curve

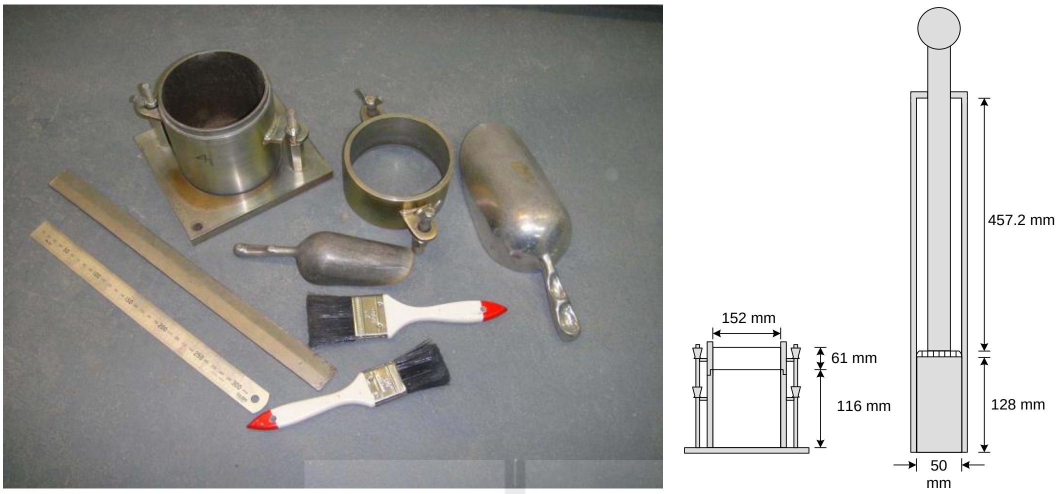

Figure 3.10 Modified Compaction Test

In this study, the compaction test was followed ASTM D1557 (2000) to determine the relationship of dry unit weight and optimum water content by using modified compaction energy since the pavement base/subbase is subjected to heavy load. The 152 mm of diameter mold, as shown in Figure 3.9 was used. The mold was connected to a base steel plate which allows the excess water drained out during compaction. There was a paper filter placed at the bottom of the mold to allow the water to drain out freely from the sample.

5kg of all blends was prepared and was mixed with different amounts of water. The samples were cured in a plastic bag over a night to ensure the uniform moisture content before compaction. The assembly of mold, which includes the mold, steel frame and base steel plate, was measured before compaction. Each blend was divided and compacted into the mold in five layers under 56 blows of 44.5N compaction effort from a drop height of 450mm, was compacted. After the compaction of 5th layer, the steel bar was used to manually trim the specimens and the small particles generated on the surface during trimming were used to fill the hole. The mass of mold and soil was measured and the mold assembly was removed from the frame, the material was extracted from the mold, weight and oven dried at 110^{o}C for 24h. The dry density and water optimum of the sample were determined and compaction curve was plotted in the relation of dry unit weight versus optimum water content.

Degradation of materials after compaction is also very important parameters for selection of pavement materials. All compacted samples of blended materials were separately collected and were performed gradation test again.

3.2.2.6 California Bearing Ratio Test

A California Bearing Ratio (CBR) test is one of input parameters for design geometry of earth structure such as road, dam and so on. ASTM D1883 (2007) indicates that California Bearing Ratio (CBR) test is a load test applied on the surface and used in soil investigation as an aid to the design of pavements. The laboratory test uses a circular piston to penetrate material compacted in a mold at a constant rate of penetration. The CBR is expressed as the ratio of the unit load on the piston required to penetrate 0.1 in (2.5mm) and 0.2 in (5mm) of the test soil to the unit load required to penetrate as standard material.

A metal cylinder mold of 152.4mm diameter and 177.8mm height, as illustrated in Figure 3.11, was used to assemble spacer disk, the steel base plate and frame. The base plate has holes uniformly spaced, which allow the water to drain out.

6kg of each blend samples was prepared and was mixed at its optimum water content only. Then, all samples were cured for a night to ensure the uniform moisture content. Afterward, samples were equally compacted under 56 blows of modified force in five layers into the CBR mold, which was assembled and inserted spacer disk over the base plate and placed filter paper on the spacer disk before compaction.

Secondly, after the fifth layer, the extension was removed and the compacted soil was carefully trimmed using the steel cutter. The patch of small hole on the surface was filled by the small particle.

Figure 3.11 Tool for CBR Test

Next, a disk of filter paper was placed on the base plate and the mold was inverted and clamped on the perforated base plate with the compacted material in contact with the filter paper. Subsequently, the surcharge of 4.54kg was placed on the surface of the compacted samples.

Finally, the samples were immersed under the water for four days (Figure 3.12) to simulate the worst-case scenario.

Figure 3.12 Immersing of CBR samples

After four days of immersion, the samples were taken out of the water for about 15minutes to allow the water to drain freely from the specimens before the start of the CBR test.

To begin the CBR test, the surcharge of weights of 4.54kg was placed on the specimen to produce an intensity of the loading specified. Next, the specimens were placed under the piston of CBR testing machine, as demonstrated in Figure 3.13.

The piston was penetrated with the smallest possible load, then the load and penetration gauges were set to zero. After that, the load was applied on the penetration piston at rate of approximately 0.05 inch or 1.27mm/min. The loads were recorded at each 0.025mm of penetration.

The relationship between penetration and applied force was plotted. The forces for 2.5mm and 5mm penetration were read from the curve.

The CBR was calculated the following formula:

$$CBR = \frac{\text{Measured Force} \times 100\%}{\text{Standard force}} \tag{3.7}$$

where standard force for 2.5mm and 5mm of penetration are 13.2kN and 19.8kN respectively. The CBR is calculated for both number of penetrations.

Figure 3.13 CBR Testing Machine

3.2.2.7 Direct Shear Test

Shear strength properties are one of important input parameters for modern geotechnical design. Once the material is used as backfill, an investigation of shear strength is very essential. To be applicable and accurate, the direct shear samples are prepared and are simulated as similar as possible to field condition. In this regards, density of the sample played the major role for direct shear test.

In this study, direct shear tests were undertaken on all RCA-CR blends by using a large-scale direct shear apparatus. The dimensions of the apparatus is 300 mm in length, 300 mm in width and 200 mm in depth. The testing apparatus is composed of two boxes; a fixed upper box and a moveable lower box as shown in Figure 3.14.

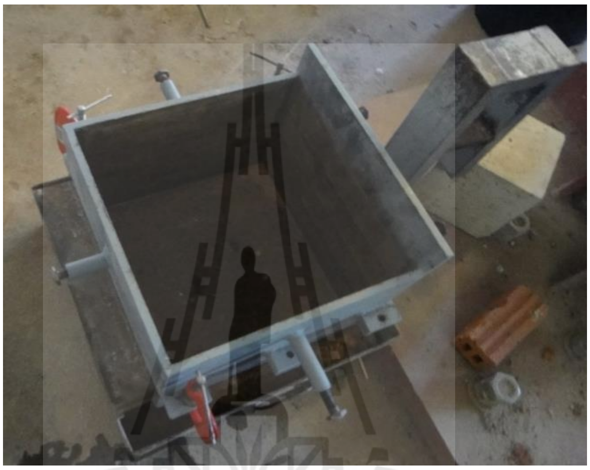

Figure 3.14 Large Direct Shear Box

The one day oven dried samples at 60^{o}c were mixed with water at optimum moisture content and kept at room temperature at 25$\pm$2 degrees for approximately 12 hours in a container to ensure that moisture is uniformly distributed in the samples.

After that, the lower and upper boxes were clamped when preparing samples for the tests. Lubricating oil was used on the platform of the shear box to reduce the friction during shearing test. The samples were compacted to 95% (±2%) of their maximum dry density ($\gamma_{d,max}$) in the shear box in four layers by using a vibratory compactor until the maximum proctor dry density was attained. Then, the sample were submerges under the water for four days to simulate the same case as CBR as Figure 3.14. To determine the Mohr-Coulomb failure envelope, the large scale Direct Shear Test (DST) was conducted on three samples of each blends at normal stress of 10 kPa, 20 kPa and 40 kPa. The horizontal displacement is about 1 mm/min to allow the water to be drained out freely. LVDTs and load cells were used to measure the horizontal, vertical displacements and shear stresses with a specialized software program as shown in Figure 3.15.

Figure 3.15 Fully Direct Shear System

Before shearing, samples were consolidated. Then, the connections between the upper and lower boxes were released, and approximately 2 mm gap between the upper and lower boxes for friction minimization was lifted up. The tests were conducted as per ASTM D5321 (2008).

The test was terminated once the horizontal shear displacement reached approximately 50 mm. The peak and critical shear strengths and dilatancy of blended materials from the large DST test were obtained from the shear stress and horizontal displacement and vertical and horizontal displacement output graphs.

CHAPTER IV

GEOTECHNICAL PROPERTIES OF RECYCLED CONCRETE AGGREGATE AND CRUSHED ROCK BLENDS

4.1 Introduction

Recycled Concrete Aggregate (RCA) was collected from Bureau of Rural Road 5, Department of Rural Road, Nakhon Ratchasima, Thailand. The mean 28 day-cube strength of the original concrete was 28.5 MPa with a standard deviator of 11.9 MPa. A basalt Crush Rock (CR) was collected from a quarry in Chockchai District, Nakhon Ratchasima, Thailand with maximum particle size of 19 mm. Both CR and RCA samples were oven-dried for 24hr at 60°C.

Physical and geotechnical tests included particle size distribution, water absorption, specific gravity, modified proctor compaction test, Los Angeles (LA), California Bearing Ratio (CBR) and direct shear, as summarized in Table 4.1. The CR and RCA with the same grain size distribution were blended to attain five different replacement ratios. Figure 4.1 shows that the grain size distribution curve of RCA and CR are between the upper and lower boundary specified by the Department of Highways, Thailand. RCA and CR have coefficient of uniformity (C_u) and coefficient of curvature (C_C) of 18.1 and 1.7 respectively. The median diameter (d_{50}) of both materials is 10 mm. Both RCA and CR are classified as well graded gravel (GW), according to Unified Soil Classification System (USCS).

Table 4.1 Summary of the test conditions

Test	Sample	Standard	Test Condition
Sieve analysis	CR : RCA 100 : 0 70 : 30 50 : 50 30 : 70 0 : 100	AASHTO T27, 2013	Dry sieve method
Specific gravity		AASHTO T85, 2004	Coarse aggregate
Water Absorption		AASHTO T85, 2004	Coarse aggregate
Los Angeles abrasion		ASTM C 131, 2006	11 steel balls and 15 minutes revolution
Compaction		ASTM D1557, 2009	Modified energy
CBR		ASTM D1883, 2007	Submerge 4 days under the water
Direct shear		ASTM D5321, 2008	σ_n =10, 20, 40 kPa

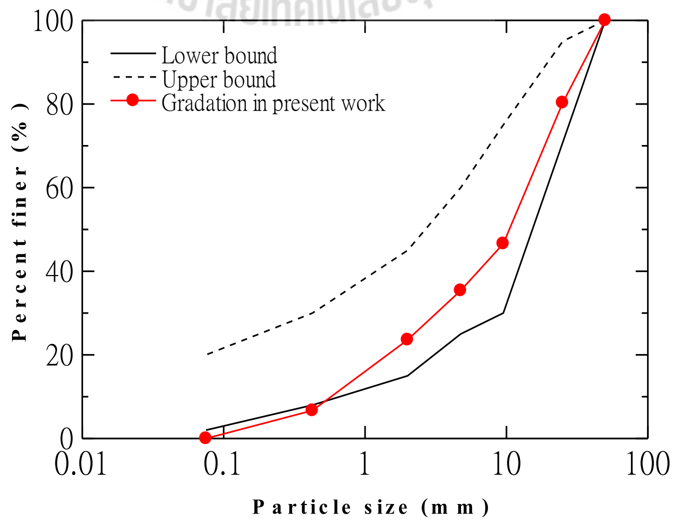

Figure 4.1 Particles Size Distribution of CR, RCA and RCA-CR blends

4.2 Test Results

4.2.1 Basic and Geotechnical Properties

Besides Los Angeles abrasion test, the durability of materials could also identified by after-compaction gradation curve. Figure 4.2 shows after- compaction gradation of RCA and CR. It is evident that the change in gradation of CR after compaction is insignificant. The gravel content decreases from 64.6% to 61.6% while sand content increases from 35.4% to 36.4% and 2.5% of clay content was found. Due to the weak mortar attached on RCA particles, the after-compaction curve of RCA is significant different from the original; i.e., gravel content decreases from 64.6% to 54.3% while sand content increases from 35.4% to 45.6%. Even with the change in gradation, the after- compaction gradation curve of both CR and RCA are still between upper and lower boundary, which meets the requirement for pavement base.

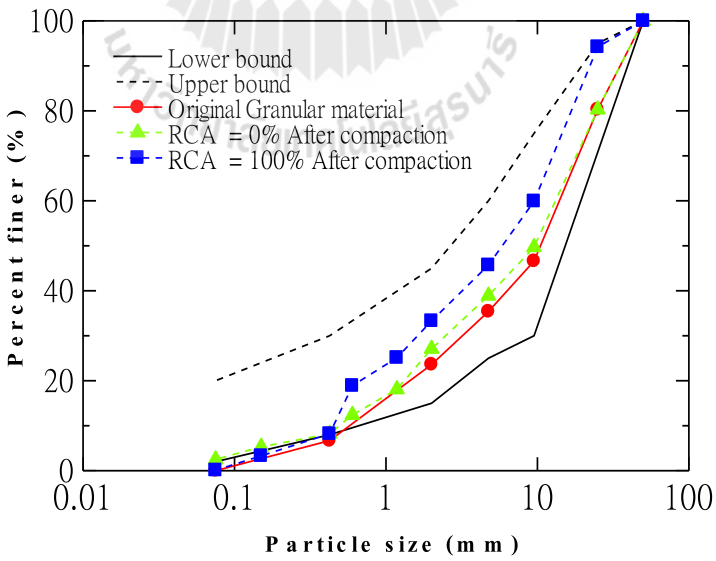

Figure 4.2 After-compaction gradation curve of CR and RCA

Table 4.2 Physical and geotechnical properties of CR and RCA blends

Engineering Properties	RCA Content					Requirement for Base Materials
	0%	30%	50%	70%	100%	
Gravel Content (%)	64.6	64.6	64.6	64.6	64.6	40-75
Sand Content (%)	35.4	35.4	35.4	35.4	35.4	23-40
Fines Content (%)	0	0	0	0	0	2-20
d_{10} Before Compaction (mm)	0.6	0.6	0.6	0.6	0.6	0- 0.83
d_{30} Before Compaction (mm)	3.2	3.2	3.2	3.2	3.2	4.3-9.6
d_{50} Before Compaction (mm)	10	10	10	10	10	2.8-17
d_{60} Before Compaction (mm)	10.5	10.5	10.5	10.5	10.5	5-20
C_u Before Compaction	18.1	18.1	18.1	18.1	18.1	-
C_c Before Compaction	1.7	1.7	1.7	1.7	1.7	-
USCS Classification	GW	GW	GW	GW	GW	-
Percent change of particle size	3	13.3	24	31.2	41	-
Specific Gravity of coarse (%)	2.81	2.79	2.78	2.77	2.75	-
Water absorption fraction (%)	2.44	3.23	3.76	3.83	4.22	-
Los Angeles Abrasion (max)	17.02	21.18	27.94	33.21	39.24	< 40
Modified: MDD (kN/m^3)	20.9	20.2	19.6	18.1	17.6	>17.5
Modified: OMC (%)	8.6	9.4	9.9	12.2	14.1	6-14
CBR (%)	128	96	68	45	36	>80

Table 4.2 shows that specific gravity of blends decreases and the water absorption increases as the replacement ratio increases due to the presence of mortar attached on RCA particles as shown in Figure 4.3. The water absorption values of RCA and CR are 4.22% and 2.44% respectively. In other words, the RCA has higher water holding capacity than CR. The increase in water absorption with RCA content is also reported by Surya et al. (2013). This because the mortar attached on the RCA particle possess a lot of void (Schutter & Audenaert, 2004), low specific gravity and high water absorption. Specific gravity value of blends ranges from 2.75–2.81, which is similar to that of natural aggregate.

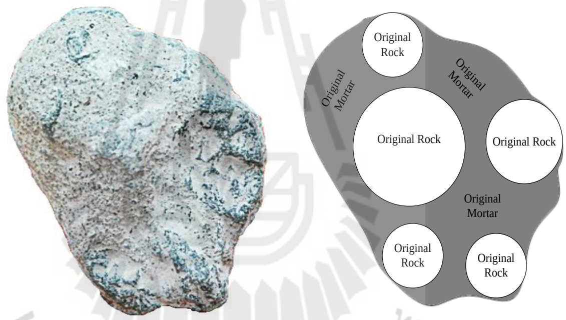

Figure 4.3 RCA's Grain Composition

Figure 4.4 shows the modified Proctor's compaction curves, measured using 152.4 mm cylindrical mold for each blend. The compaction curves are different even though the RCA and CR have same initial gradation. Optimum Water Content (OWC) increases while maximum dry density ($\gamma_{d,max}$) decreases with increasing replacement ratio. The increase in OWC with replacement ratio is due to the increase in water holding capacity caused by the increase in water absorption. Even though the water absorption of RCA is high, the value is still within the limitation for base materials.

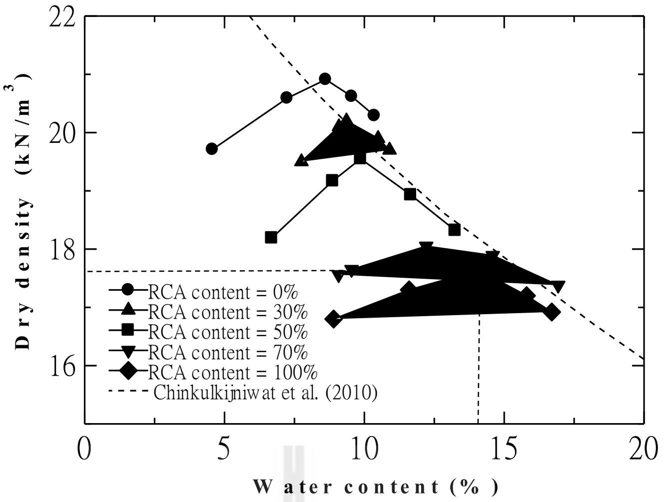

Figure 4.4 Compaction curves of each blend

OWC and dry density ($\gamma_{d,max}$) values are within the typical range requirement for road base/subbase materials ($\gamma_{d,max}$ > 17.5 kN/m^3 and 6%< OWC < 14%) (Rahman et al., 2014).

Chinkulkijniwat et al. (2010) proposed a predictive equation between maximum dry density (MDD) ($\gamma_{d,max}$) and optimum water content (OWC). The equation is represented as the dash line in Figure 4.4. The measured ($\gamma_{d,max}$ and OWC) points for each blend more or less lie on the proposed line, indicating that the $\gamma_{d,max}$ for each blend can be approximated from OWC or vice versa. The slight difference is possibly due to the lower specific gravity value of RCA particles. The Chinkulkijniwat et al.'s equation was developed based on the natural soils whose specific gravity values are approximately 2.7. As such, the predicted $\gamma_{d, max}$ value is higher than the measured ones for high OWC (higher RCA content) values.

Los Angeles (LA) abrasion test is used to determine the resistance of aggregate by abrasion and impact forces. LA abrasion is one of the most significant parameters for selecting pavement materials. The lower LA abrasion value, the longer the service life. LA abrasion of smaller than 60%, 40% are required for subbase and base, respectively (Arulrajah et al., 2014; Arulrajah et al., 2013; Arulrajah et al., 2013; DH-S, 1996). Table 4.2 shows that with the increase of RCA content from 0% to 100%, LA abrasion values increase from 17.02% to 39.24%. CR has low LA abrasion value whereas LA of RCA is the highest, due to the weakness mortar attached on the RCA particles. The result indicates that the abrasion of all blends meets the requirement for base material.

In a geometry design, CBR is the key parameter for determining the thickness of pavement structure. The replacement ratio significantly affects CBR value. Table 4.2 shows that CBR decreases with increasing replacement ratio. CBR varies from 36% to 128% for RCA content ranging from 0% to 100%.

Since the requirement of CBR value for base material is different from countries to countries. In Thailand and UK, CBR value of 80% requires for base pavement (Melbouci, 2009; Overseas Road Note 31, 1993) and 25% for sub-base (Donrak & S.Horpibulsuk, 2014). It is evident from this study that the CBR value of CR and the blend with 30% replacement ratio meets this requirement for base material. The CBR values of the other test blends meet standard requirement of subbase material.

Based on test results of grain size distribution, water absorption, Los Angeles abrasion, and California Bearing Ratio, the blends with 30% of replacement is found to have geotechnical properties suitable for base materials, while the blends with 70%, 50% and 100% replacement are suitable for subbase and footpath pavement, respectively.

4.2.2 Shear Strength

Shear strength properties are one of important input parameters for geotechnical design. The peak and critical shear strengths of the blends were obtained from the large DST test.

Figure 4.5 shows that the shear responses of the test materials are in similar pattern and typical of coarse-grained materials. The strain-softening behavior is found in stress and strain relationship. Shear stress increases up to a peak stress (τ_p) states after that decreases and levels off at a critical shear stress (τ_{cr}) state. This strain softening is associated with the dilatant behaviors as seen in the relationship between vertical displacement and horizontal displacement. The samples exhibit a slight compression initially after shearing and then decreases with an increase in horizontal displacement. The maximum dilatancy ratio, the ratio of vertical displacement to horizontal displacement, is found to be at the peak shear stress. At the critical state in shear stress and horizontal displacement relationship, the change in vertical displacement approaches zero.

The effect of RCA replacement on the shear response is clearly shown in Figure 4.5. The strain- softening behavior is clearly observed for CR (Figure 4.5a) while it minimizes for RCA. In other words, the shear strength difference between the peak state and critical state (τ_p-τ_{cr}) reduces with RCA replacement ratio. Since the replacement ratio of RCA is associated with lower degree of strain softening. The relationship between maximum dilatancy and RCA replacement ratio for various confining pressures is shown Figure 4.6.

The dialatancy ratio decreases with an increase of effective normal stress. At a given normal stress, the maximum dilatancy ratio decreases with increasing RCA replacement ratio in a linear function. The lower dilatancy ratio results in the lower vertical strain at the critical state.

Since the initial gradation of RCA and CR is the same, the reduction in interlocking induced shear strength is mainly caused by the crushing of RCA particles during compaction. The larger difference in shear strength (τ_p - τ_{cr}) indicates the larger resistance to particles crushing. The particle crushing can be illustrated by the comparison of gradation curves before and after compaction. The median diameter d_{50} is used as a reference for this comparison.

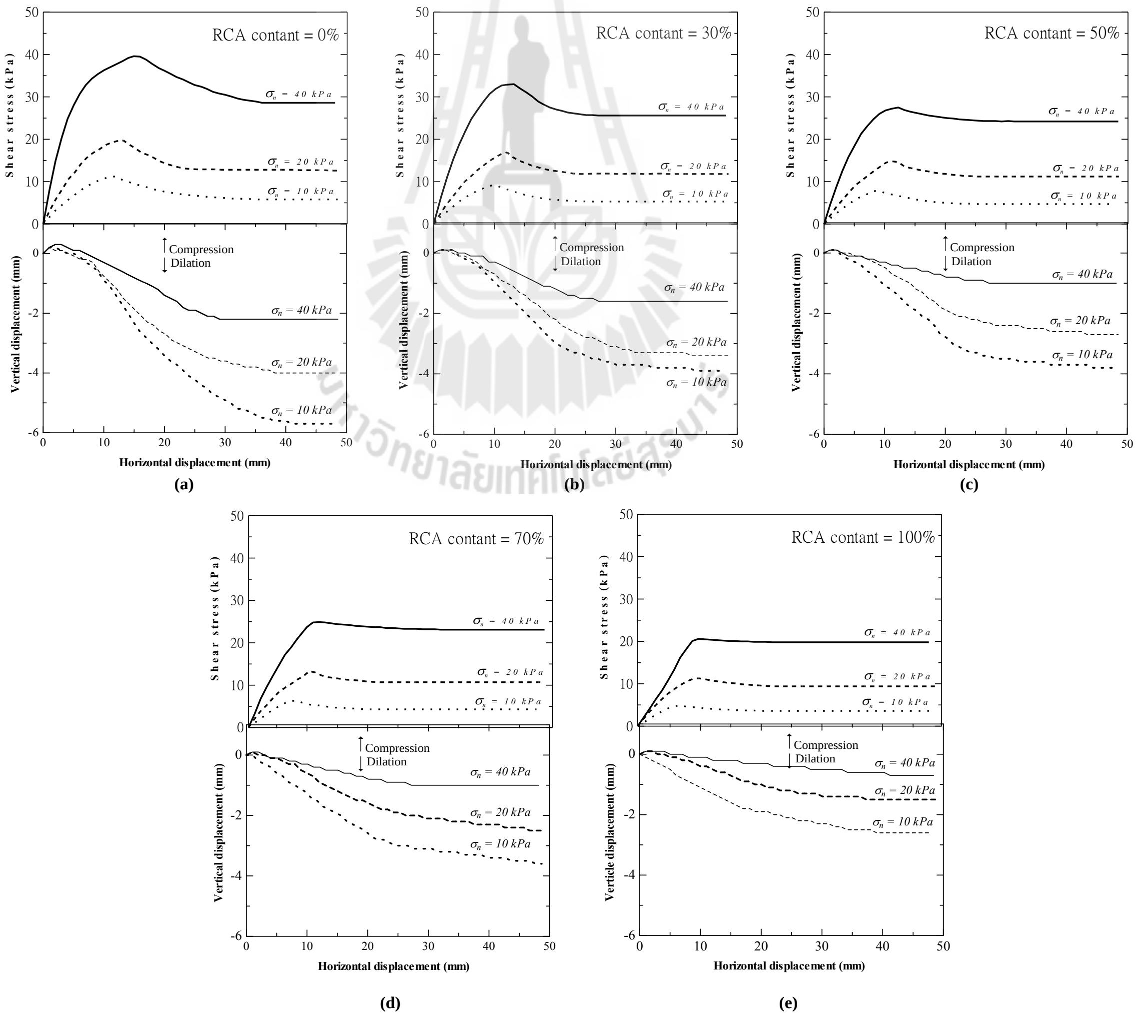

Figure 4.5 Shear response of specimens

The crushing index, C is thus defined as the change in d_{50} before and after compaction in the form:

$$C = \frac{d_{50}^{b} - d_{50}^{a}}{d_{50}^{b}} \times 100 \qquad (4.9)$$

where d_{50}^{b} and $d_{50}^{b}$are median size before and after compaction, respectively. The C value varies from 3% to 42% for RCA replacement ratio, ranging from 0% to 100% as shown in Figure 4.7. The relationship between C and RCA is represented by a linear function. This means the degree of crushing of mortar due to compaction is directly related to RCA replacement ratio. The higher degree of crushing reduces the interlocking among the particles and hence lower dilatancy ratio and peak strength. The previous test results show that LA abrasion of the blend materials after compaction increases while CBR decrease as the RCA replacement ratio increases. In other words, the strength of RCA particles decrease as the RCA replacement increases.

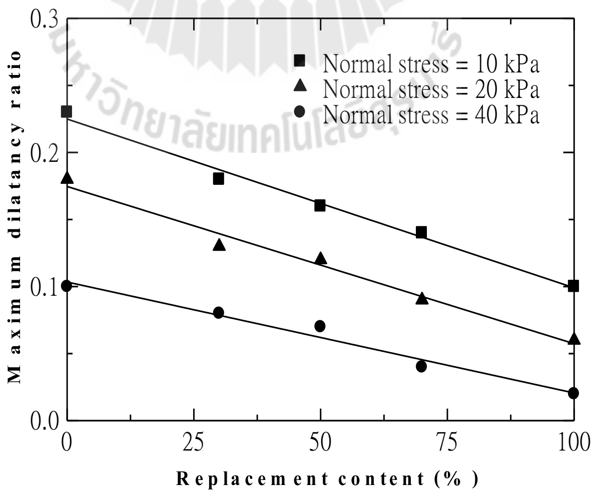

Figure 4.6 Relationship between maximum dilatancy ratio and replacement content

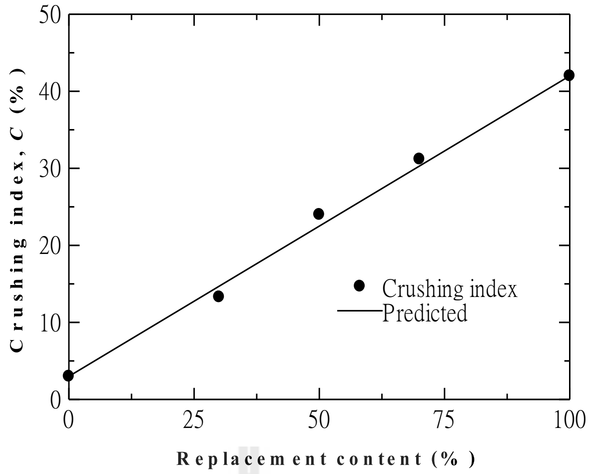

Figure 4.7 Relationship between crushing index and replacement ratio

The shear strengths at both peak and critical states increase with increasing normal stress as shown in Table 4.3, which is typical of coarse-grained materials under drained shearing. The effect of normal stress on the shear strength is clearly illustrated by the gradient of failure envelop (friction angle).

Table 4.3 Shear strengths parameters of each tested blend

Properties	RCA Content				
	0%	30%	50%	70%	100%
Cohesion	0	0	0	0	0
Peak internal friction angle	43.4	38.4	33.1	31.8	27.6
Critical internal friction angle	37.2	34.1	33.0	32.1	28.4

The Mohr-coulomb failure envelops for peak and critical stress are shown in Figure 4.8. The failure envelopes show that all the blends are fictional material without cohesion due to insignificant fine particles. The highest peak friction angle (ϕ_p) is found for CR due to the highest dilatancy ratio (interlocking effect). The peak friction angle decreases with RCA replacement ratio due to a reduction in interlocking effect and the lowest ϕ_p is found for RCA. The critical state friction angle ϕ_{cr} of geomaterial is intrinsic and controlled by the gradation and particle strength. Due to the smaller particle size and lower particle strength of RCA, the ϕ_{cr} value of the blends decrease with RCA replacement ratio. In addition, the difference between ϕ_p and ϕ_{cr} ($\Delta\phi$) is noticed in Figure 4.8.

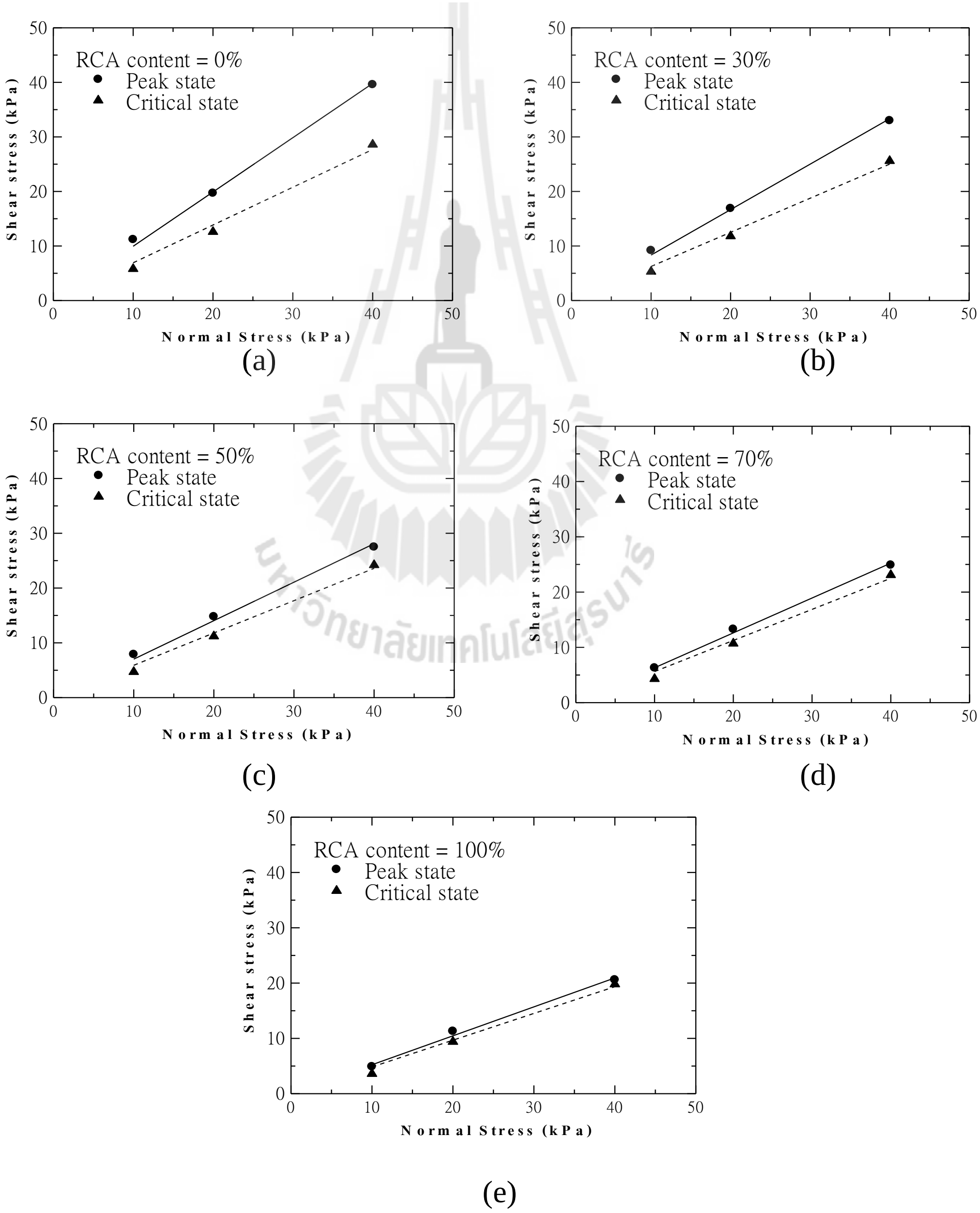

Figure 4.8 Failure envelops of specimens

The difference is minimal for RCA, indicating that the high degree of crushing due to compaction masks the interlocking of the RCA. The fiction angle of RCA is lower than the typical requirement for pavement base of 35 degrees. The increase in interlocking effect by addition of CR can improve the peak friction angle.

4.2.3 Prediction

Based on the analysis of water absorption of all blends above, the predictive equation for water absorption is proposed in linear function of replacement ratio as shown in Figure 4.9.

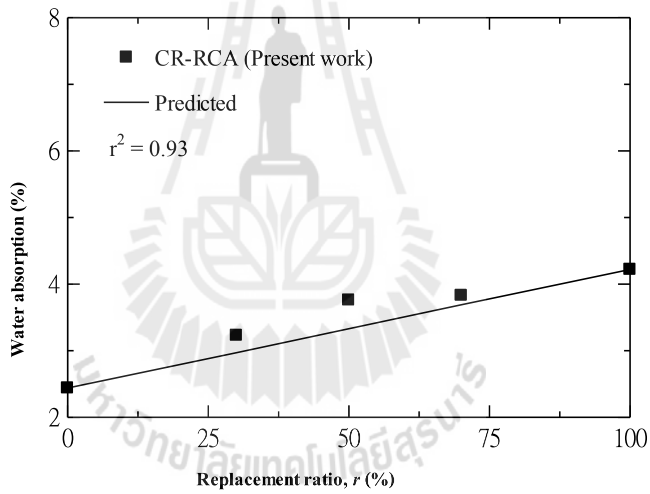

Figure 4.9 Relationship of Replacement Ratio and Water Absorption

The relationship between water absorption and replacement ratio for CR-RCA blends is presented as follows:

$$WA_X = a + b.\, r_x \tag{4.1}$$

where WA_x : Water absorption of different replacement ratio

r_x : replacement ratio

a, b : constants

To determine parameters *a* and *b*, the approximation from two conditions is used:

- ❖ At 0% of replacement ratio

$$a = WA_0 \tag{4.2}$$

- ❖ At 100% of replacement ratio

$$b = \frac{WA_0 - WA_{100}}{100} \tag{4.3}$$

Similarly, from laboratory test above, Figure 4.10 shows that Los Angeles abrasion value of blends linearly increases and the predicted equation is proposed as follows:

$$LA_x = c + d \cdot r_x \tag{4.4}$$

where:

LA_x : LA abrasion value at any replacement ratio,

r_x : Replacement ratio

c, d : Constants.

Both c, d could be determined by two conditions:

- ❖ 0% of replacement ratio

$$c = LA_0 \tag{4.5}$$

❖ 100% of replacement ratio

$$d= -\left(\frac{LA_0 - LA_{100}}{100}\right) \tag{4.6}$$

where LA_0 and LA_{100} are the abrasion at 0% and 100% replacement ratios, respectively.

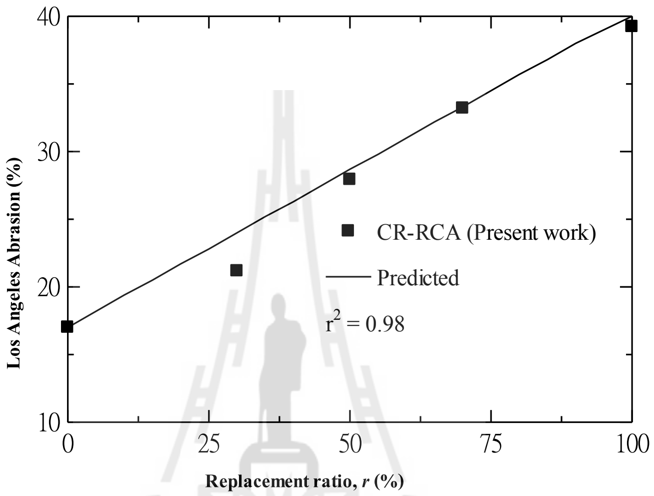

Figure 4.10 Relationship between replacement content and LA abrasion

Figure 4.11 shows the relationship between CBR value and replacement ratio. CBR value exponentially decreases with the increase of replacement ratio, because recycled concrete aggregates have a larger amount of porosity and can potentially undergo a higher degree of deformation (Arulrajah et al., 2014).

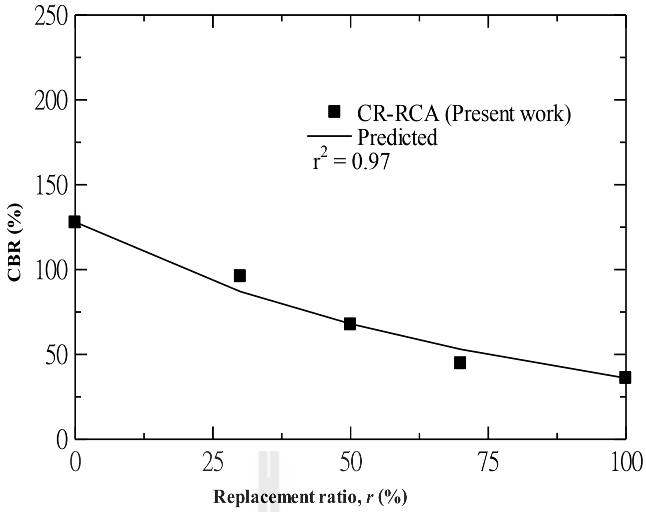

Figure 4.11 Relationship between replacement content and CBR

From laboratory results in accordance to ASTM D1883 (2007) above, the predicted equation of CBR at any replacement ratio is proposed:

$$CBR_x = e\left[\exp(-f.r_x)\right] \quad (4.6)$$

where CBR_x is California Bearing Ratio at any replacement content.

Again, e and f are constant and determined using the two conditions:

❖ 0% of replacement ratio

$$e = CBR_0 \quad (4.7)$$

❖ 100% of replacement ratio

$$f = -\left(\frac{\ln\left(\frac{CBR_{100}}{CBR_0}\right)}{100} \right) \quad (4.8)$$

where CBR_0 and CBR_{100} are CBR value at 0 and 100% replacement ratios, respectively.

From the shear strength analysis of all blends, it is found that as the RCA replacement ratio increases, peak and critical state friction angles linearly decrease as shown in Figure 4.12. The linear change between peak and critical state friction angles versus RCA replacement ratio might be due to the linear effect of RCA replacement on the dilatancy and crushing index as shown in Figures 4.9 and 4.10.

The relationship between ϕ_p and ϕ_r versus RCA replacement ratio can be presented in the form:

$$\tan\phi = gr_X + h \tag{4.10}$$

where: r_x : replacement ratio

g and h: constants

Constants g and h are approximated from the test result:

❖ At replacement ratio of 0%

$$h = \tan\phi_0 \tag{4.11}$$

❖ At replacement ratio of 100%

$$g = -\left(\frac{\tan\phi_0 - \tan\phi_{100}}{100}\right) \tag{4.12}$$

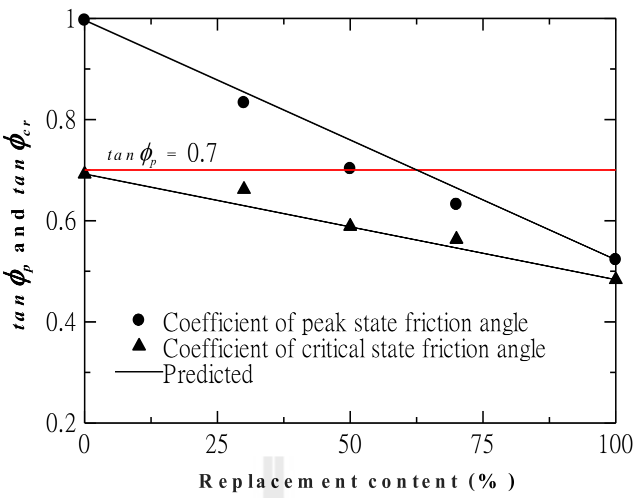

Figure 4.12 Relationship between ϕ_p and ϕ_{cr} and Replacement ratio

4.2.4 Verification

Based on the analysis of the physical and geotechnical properties of the blends, it is found that as the replacement ratio increases, water absorption and LA abrasion linearly increase while CBR decrease exponentially. The predictive equations of water absorption, LA abrasion, and CBR were thus proposed equations. To verify the proposed equations of water absorption, Los Angeles, and California Bearing Ratio, the available test data on RCA-Crushed Brick (CBR) and CR-CB blends from Arulrajah, Piratheepan, Bo, et al. (2012) are taken and predicted even though their materials were blended with different grain size distribution and different type of materials.

Based on equation 4.1, *a* and *b* are 2.4 and 0.018, 4.7 and 0.015, 3.3 and 0.028 for CR-RCA, RCA-CB and CR-CB blends, respectively;

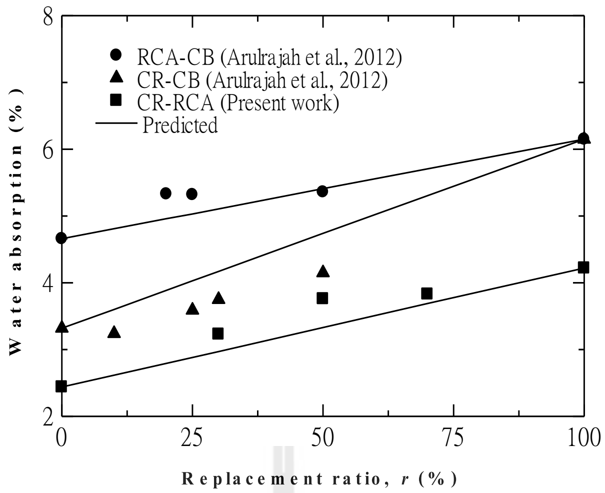

Figure 4.13 Relationship between replacement content and Water absorption

From equation 4.4, *c* and *d* are 17 and 0.22, 28 and 0.08, 21 and 0.15 for CR-RCA, RCA-CB and CR-CB blends, respectively.

From equation 4.7, *e* and *f* are 127.8 and -0.013, 203.8 and -0.005, 160.0 and -0.003 for CR-RCA, RCA-CB and CR-CB blends, respectively.

g and *h* for RCA-CR blends are 2.4 and -0.18, respectively. This equation is useful to predict the optimum replacement content, which provides the required peak state friction angle.

Using the constants *a* to *f*, Table 4.4 shows the prediction of water absorption, LA abrasion and CBR for RCA-CB and CR-CB blends and compared with measured ones.

Figure 4.13 shows the predicted water absorption versus replacement ratio relationship of replacement. Figure 4.14 shows the predicted Los Angeles abrasion versus replacement ratio. Figure 4.15 shows the predicted CBR value versus replacement ratio.

Table 4.4 Comparison between measured and predicted value

Materials	Replacement Ratio (%)	Properties (%)								
		WA		E	LA		E	CBR		E
		M	P		M	P		M	P	
RCA-CB	0	4.66	4.66	0	28	28	0	160	160	0
	15	NA	NA	NA	31	29	6	NA	NA	NA
	20	5.33	4.96	7	30	30	1	NA	NA	NA
	25	5.32	5.03	5	30	30	0	141	150	6
	40	NA	NA	NA	32	31	3	134	144	7
	50	5.36	5.41	1	33	32	3	131	140	7
	100	6.15	6.15	0	36	36	0	123	123	0
CR-CB	0	3.32	3.32	0	21	21	0	204	204	0
	10	3.24	3.6	11	22	23	2	NA	NA	NA
	15	NA	NA	NA	21	23	11	173	189	9
	20	NA	NA	NA	NA	NA	NA	168	184	10
	25	3.59	4.03	12	23	25	8	NA	NA	NA
	30	3.75	4.17	11	27	26	6	166	175-167	6
	40	NA	NA	NA	NA	NA	NA	153	167	9
	50	4.15	4.47	14	29	29	2	127	158	25
	100	6.15	6.15	0	36	36	0	123	123	0
CR-RCA	0	2.44	2.44	0	17	17	0	128	128	0
	30	3.23	2.97	8	21	24	12	96	87	9
	50	3.76	3.33	11	28	28	1	68	68	0
	70	3.83	3.69	4	33	33	2	45	53	18
	100	4.22	4.22	0	39	39	0	36	36	0
Mean absolute of percentage error		5.33			3.0			6.6		

Note: M: measured; P: Predicted; E: Error

The predicted and measured data are in a good agreement, reinforcing the applicability of the proposed equations.

The prediction error is possibly due to the equations being developed from the blends with the same gradation. However, the error is less than 10% and it is acceptable for engineering practice with mean absolute percent error of less than 5.3%, 3.0% and 6.6% for WA, LA abrasion and CBR, respectively.

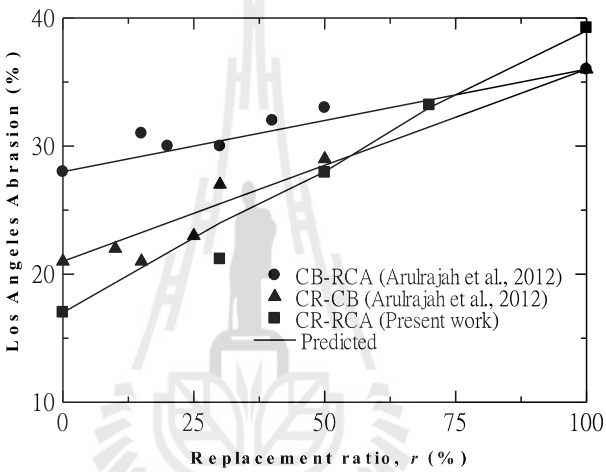

Figure 4.14 Relationship between replacement content and Los Angeles abrasion

The mean absolute percent error is calculated by following equation.

$$\frac{\sum\left|\frac{A_m - A_p}{A_p}\right|}{n}\times 100 \qquad (4.13)$$

where A_p : predicted values

A_m : measured values

n : number of data.

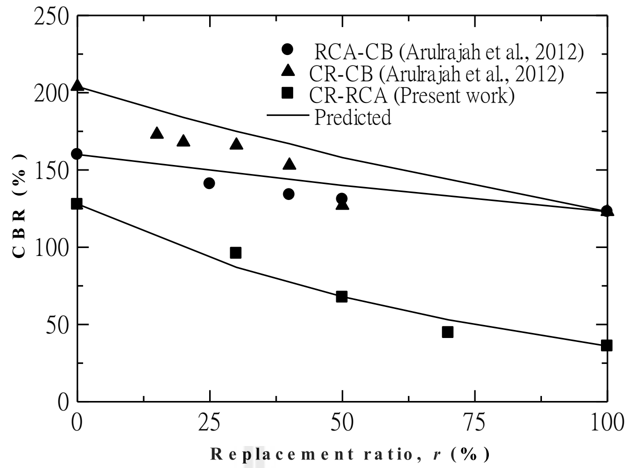

Figure 4.15 Relationship between replacement content and CBR value

Shear Strength Parameters

To extend the proposed equations for predicting friction angle of other blended materials, the available test data on CR-Reclaimed asphalt pavement (RAP) and Pit run-RAP blends from final report of Mokwa and Peebles (2005) are taken to examine the applicability of proposed equation even though their materials were blended with different grain size distributions of each original material.

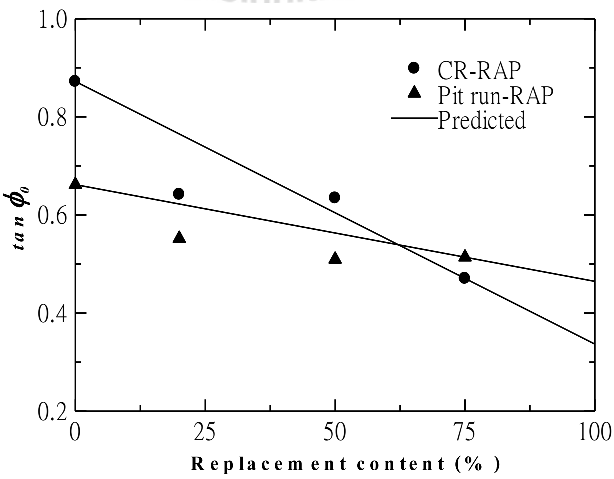

Figure 4.16 Predicted friction angle of CR-RAP and Pit run-RAP blends

Figure 4.16 shows the relationship between friction angle and replacement ratio of CR-RCA blends and CR-CB blends when ϕ_0 is the equivalent friction angle at a confining pressure of 24.8 kPa. Based on the proposed equations, *g* and *h* are 44.9 and -0.21 for RCA-RAP blends and 41.1 and -0.10 for Pit run-RAP blends. It is evident in Figure 4.16 that the predicted and measured data are in a good agreement, reinforcing the applicability of the proposed equations.

The prediction error is possibly due to the proposed equations being developed from the blends with the same gradation of RCA and CR. However, the error is acceptable for engineering practice with a mean absolute percent error of less than 4.9%.

Suggested method to approximating strength parameters of RCA-CR blends for different RCA replacement ratios

1. Perform the compaction test and determine the maximum dry density and optimum water content of the blended materials at 0% and 100% replacement ratios.
2. Determine the friction angles of the blended materials at 0% (ϕ_0) and 100% (ϕ_{100}) replacement ratios. at
3. Calculate the constants *g* and *h* by using Equations (4.11) and (4.12).
4. Back calculate the obtained r_x (optimum replacement ratio) by substituting required $\tan\phi$ in Eq.(4.11).
5. Perform direct shear test on samples at optimum replacement ratio to verify the approximated value.

CHAPTER V

CONCLUSIONS

The physical and geotechnical properties including gradation, specific gravity, compaction, water absorption, LA abrasion, CBR and shear strength of the crushed rock (CR) and recycled concrete aggregate (RCA) blends are investigated and analyzed in this research.

Due to effect of attached mortar around RCA particles, RCA has high water absorption, high Los Angeles value and low CBR value, which could not meet the standard requirement for base layer. In order to meet requirement for pavement base, RCA was blended with CR. It is found that geotechnical properties of blend with 30% RCA replacement meets the requirement for base materials.

All physical and geotechnical properties are found to be dependent on replacement ratio. The increment of RCA content leads to have low specific gravity, high water absorption, and high Los Angeles abrasion value. Similarly, the CBR and shear response of the specimens decrease as increase of replacement ratio.

5.1 Physical Properties

It is concluded from this research that all physical properties are depended on replacement content. Based on the analysis of the physical properties of the CR-RCA blends, the predictive equations for water absorption, LA abrasion are proposed in term of replacement ratio in linear function. The available test data of RCA-CB and CR-RCA blends were taken to validate the proposed equations. The predicted and measured data are in good agreement with low mean absolute percent error. The prediction error is possibly because the equations were proposed on the CR-RCA blends with the same gradations of CR and RCA. These proposed equations are considered as useful for geotechnical and pavement practitioners for pavement design and selection of pavement materials.

5.2 Geotechnical Properties

CBR value of the specimens decreases as increase in replacement ratio. The decreases of CBR value might be caused by high water absorption and LA abrasion value of RCA particles. From analysis of CBR value of the CR-RCA blends, the predictive equation for CBR is proposed in term of replacement ratio in exponential function. To validate equation, the existing test data of RCA-CB and CR-RCA blends are also used. The prediction error is acceptable since it is less than 10%. This might be because of the same reasons to water absorption and LA abrasion. The specimens were prepared with same gradation of RCA and CR.

Shear response of RCA-CR blends at different RCA replacement ratio was also investigated. All shear response of the test materials are similar to coarse-grained materials. The effect of RCA replacement on the shear response shows that the strain-softening behavior is clearly observed for CR while it minimizes for RCA. The shear strength difference between the peak state and critical state (τ_p- τ_{cr}) reduces with RCA replacement ratio, which is associated with the decrease in maximum dilatancy ratio at a given normal stress. The lower dilatancy ratio results in the lower vertical strain at the critical state. This implies that the strength of blended particles decreases as the RCA replacement increases. Since the initial gradation of RCA and CR is the same, the reduction in dilatancy induced shear strength is mainly caused by the crushing of RCA particles during compaction.

From the analysis of the test results, the linear relationship between tanϕ and replacement ratio is proposed. The relationship can be extended to predict the friction angles of other blended materials with an acceptable error. The accuracy of the prediction is dependent on the grain size distribution of two materials. The larger difference in grain size distribution results in the higher error.

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APPENDIX A

PUBLICATION

Publication

Chea, S., Prongmanee, N., Choenklang, P., Horpibulsuk, S., and Arulrajah, A., (2014), **Assessment of Physical and Geotechnical Properties of Recycled Concrete Aggregate and Crushed Rock blends.** International Conference on Advances in Civil Engineering for Sustainable Development, Suranaree University of Technology, Nakhon Ratchasima, Thailand, August 27^{th}-29^{th}, 2014, Vol. 2, pp. 177-183.

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Assessment of Physical and Geotechnical Properties of Recycled Concrete Aggregate and Crushed Rock Blends

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ABSTRACT: The usage of blends of CR and Recycled Concrete Aggregate (RCA) of the same particle size in pavement application reduces the demand of natural materials. The physical and geotechnical properties of RCA-CR blends are investigated and analyzed in this paper. The increase of RCA content results in the increase in Optimum Water Content (OWC) due to the high water absorption of mortar of RCA particles. Due to the low strength of RCA particles, Loss Angeles (LA) abrasion increases with increasing RCA content. The results show that RCA-CR blends can be used as sub-base and base materials, where their LA abrasion varies from 17- 39%, water absorption from 2.4 - 4.2% and CBR from 36 - 128% for RCA replacement ranging from 30 to 100%. The relationship between LA abrasion, water content and CBR versus RCA replacement is proposed, which is useful to geotechnical and pavement practitioners for selection of pavement materials and pavement design.

1 INTRODUCTION

Granular materials are increasingly being used for pavement applications. Subsequently, large amount of natural resources are being consumed everyday by human's activities. Meanwhile, large amount of waste material is generated and disposed back to the environment. The construction sectors generate large amount of Recycled Concrete Aggregate (RCA) from demolition of buildings and reconstruction of concrete pavements (Puppala et al. 2012; Saride et al. 2010 and Rodgers et al. 2009). RCA is increasing globally due to rapid increase in construction and demolition activities in construction sector.

To reduce the usage of natural resource and to reduce the waste disposed to the environment, recycled materials are being increasingly used by the infrastructure sector. There has been an extensively interest in the usage of RCA in both pavement base and subbase applications (Arulrajah et al., 2013). Several researchers have reported on the usage of RCA for pavement applications (Poon and Chan, 2006, Azam and Cameron, 2012, Gabr and Cameron, 2012; Arulrajahet al., 2012). The reuse of RCA will reduce the demand of natural materials, and will reduce waste, which is generally destined to landfill (Ali et al. 2011a; Tam and Tam 2006). The usage of recycled material will significantly reduce carbon footprints and to sustain environment (Disfani et al. 2012; Tam 2009). Arulrajah et al. (2013) have reported that RCA exhibits low water absorption and Los Angeles abrasion and high CBR values that meet the requirement for pavement subbase layer; however, the physical and geotechnical properties of RCA are unsuitable for base layer.

In order to meet the requirement for base materials, RCA might be blended with high quality materials. Crushed rock (CR) could be considered as a high quality material. The engineering properties of pavement materials are generally controlled by gradation and strength of particles; therefore the blends in this study were prepared from the same gradation of RCA and CR, which has not been previously investigated. The assessment of geotechnical properties of blends at different proportions is important for pavement design and for selection of pavement materials, which is the focus of this paper. The assessment is performed using engineering properties of RCA and CR as references. The outcome of this research is useful as fundamental for further study on suitable green pavement materials.

2 MATERIALS AND METHODS

2.1 *Materials*

RCA was collected from Bureau of Rural Roads 5, Department of Rural Roads, Nakhon Ratchasima, Thailand. The mean 28 day-cube strength of the original concrete was 28.5 MPa with standard deviation of 11.9 MPa. RCA was passed through various sieves and stored for adjustment of the RCA gradation to meet the specification by Department of Highways and Department of Rural Road. Crush Rock (CR) was collected from a quarry from Chokchai District, Nakhon Ratchasima, Thailand. It was sourced from a basalt rock with a maximum particle size of 19 mm. Both CR and RCA samples were oven-dried for 24 hr at 60°C. It is found that the grain size distribution curve of CR is consistent with the requirement of Department of Highways. The gradation of RCA was adjusted to be the same as that of CR. The RCA was blended with CR at replacement ratios of 100%, 70%, 50% and 30%.

2.2 *Test method*

Physical tests were undertaken on RCA, CR and RCA-CR blends. Physical and geotechnical tests included particle size distribution, water absorption, specific gravity, modified Proctor compaction test and Los Angeles (LA) abrasion. The particle size distribution of the samples, which is the principal parameter controlling strength of material, was conducted according to ASTM D422- 63(2007). It was found that the maximum size of aggregates was 19 mm. Modified Proctor compaction tests were conducted according to ASTM D1557 (2009) to determine the maximum dry density and optimum water content. The 6 inch or 152.4 mm cylindrical mold was used for this modified compaction. A California Bearing Ratio (CBR) test is one of the input parameters for designing geometry of earth structure such as road, dam and so on. According to ASTM D1883 (2007), the specimens were compacted with modified Proctor compaction energy at the optimum water content (OWC) and submerged under water for 4 days to simulate a worst case scenario.

Table 1. Result of basic properties.

Engineering Properties	RCA Replacement					Requirement for Pavement Base Materials
	0%	30%	50%	70%	100%	
Gravel Content Before Compaction (%)	64.6	64.6	64.6	64.6	64.6	40-75
Sand Content Before Compaction (%)	35.4	35.4	35.4	35.4	35.4	23-40
Fines Content Before Compaction (%)	0	0	0	0	0	2-20
d10 Before Compaction (mm)	0.6	0.6	0.6	0.6	0.6	0- 0.83
d30 Before Compaction (mm)	3.2	3.2	3.2	3.2	3.2	4.3-9.6
d50 Before Compaction (mm)	10	10	10	10	10	2.8-17
d60 Before Compaction (mm)	10.5	10.5	10.5	10.5	10.5	5-20
Cu Before Compaction	18.1	18.1	18.1	18.1	18.1	-
Cc Before Compaction	1.7	1.7	1.7	1.7	1.7	-
USCS Classification Before Compaction	GW	GW	GW	GW	GW	-
Percent change of particle size (%c)	3	13.3	24	31.2	41	-
Specific gravity of coarse fraction	2.81	2.79	2.78	2.77	2.75	-
Water absorption coarse fraction (%)	2.44	3.23	3.76	3.83	4.22	-
Los Angeles Abrasion (max)	17.02	21.18	27.94	33.21	39.24	< 40
Modified Compaction: Max dry density (kN/m^3)	20.9	20.2	19.6	18.1	17.6	>17.5
Modified Compaction: Optimum moisture content (%)	8.6	9.4	9.9	12.2	14.1	6-14
CBR (%)	128	96	68	45	36	>80

3 TEST RESULTS

Particle density and water absorption tests were carried out according to ASTM C127-88 (2001). Los Angele abrasion test was conducted according to ASTM C131 (2006) to determine the resistance of aggregate by abrasion and impact forces.

Table 1 shows the physical and geotechnical properties of each blend. The gradation data (Table 1) and grain size distribution (Figure 1) show that the RCA and CR are between the upper and lower boundary specified by Department of Highways, Thailand (DH-S 201/2544). It is noted that the gradation of CR and RCA are suitable as pavement base. RCA and CR have coefficient of uniformity (C_u) and coefficient of curvature (C_c) of 18.1 and 1.7 respectively. The median diameter (d_{50}) of both materials is 10 mm. RCA and CR are classified as well graded gravel (GW) according to Unified Soil Classification System (USCS).

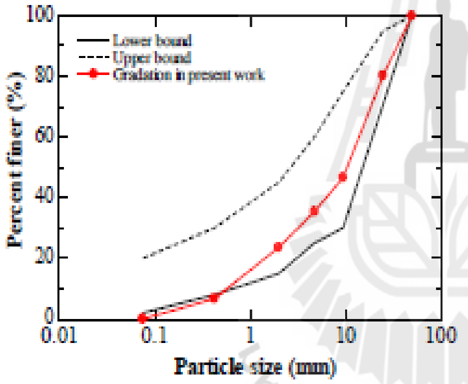

Figure 1. Particle size distribution of CR, RCA and RCA-CR blends.

Specific gravity of blends decreases as the replacement ratio increases due to the low specific gravity of mortar attached on RCA particles. The compaction curves for each blend are different even though they have same gradation (Figure 2). The Optimum Water Content (OWC) increases while maximum dry density ($\gamma_{d,max}$) of the blends decreases with increasing replacement ratio. This might be because the mortar on the RCA particles has lower lower specific gravity. The OWC and $\gamma_{d,\ max}$ values are within the typical range requirement for road base/subbase materials ($\gamma_{d,\ max}$ > 17.5 kN/m^3 and 6% < OWC < 14%) (Rahman et al., 2013). In Figure 2, the predictive equation between $\gamma_{d,max}$ and OWC proposed by Chinkulkijniwat et al. (2010) is plotted and compared with the test data of different blends. The equation can fit the test ($\gamma_{d,max}$ and OWC) data well. The slight difference is possibly due to the lower specific gravity of the RCA particles. The Chinkulkijniwat et al.'s equation was developed based on the natural soils whose specific gravity values are approximately 2.7. As such, the predicted $\gamma_{d,max}$ values are higher the measured ones for high OWC (higher RCA content) values.

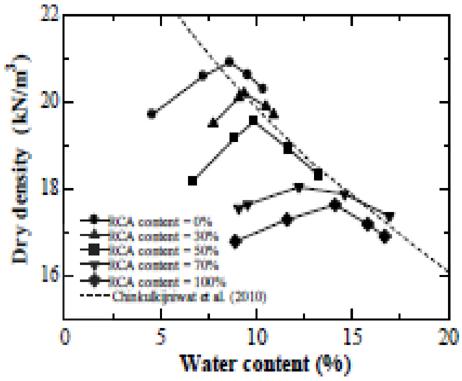

Figure 2. Compaction curve.

The test data on water absorption (Table 1) show that the water absorption of the blends increases as RCA content increases. This is because the mortar attached on the RCA particles possesses a lot of voids (Schutter and Audenaert 2004). In other words, the water holding capacity of RCA is higher than CR. The water holding capacity generally controls OWC of compacted materials. The higher the water holding capacity, the greater the OWC. As such, the OWC increases with increasing replacement ratio (refer to Figure 2). The water absorption increases linearly from 2.4% to 4.2% for RCA content from 100% to 0%.

LA abrasion is one of the most significant parameters for pavement design. The lower the LA abrasion, the longer the service life. LA abrasion of smaller than 60% and 35% are required for subbase footpath and base materials, respectively (Arulrajah et al., 2013 and 2014). Table 1 shows that the LA abrasion value increases linearly with the RCA content due to weakness of mortar attached on the RCA particles. The LA abrasion value varies from 17% to 39% for RCA contents ranging from 0% to 100%. The results show that the abrasion for the blends meets the requirement for subbase, footpath and base materials.

In a geometry design, CBR value is the key parameter for defining the thickness of pavement structure materials. The replacement ratio significantly affects CBR value. The result shows that CBR decreases with increasing replacement ratio. The CBR varies from 36% to 128% for RCA contents ranging from 0% to 100%. Horpibulsuk et al. (2013) have established a linear relationship between maximum dry density and CBR value. It is found from this study that the maximum dry density ($\gamma_{d,max}$) of the blends decreases with an increase of replacement content. Therefore, the CBR of blends is possibly controlled by replacement content. Similarly, different country has different specification. According to ODA (1993), mentioned that the minimum value of CBR for base material is 80%. Therefore, The CBR values for crushed rock and the blends with replacement ratios less than 30% are higher than 80%, which meets the requirement for base materials.

4 ANALYSIS

Based on the analysis of the physical and geotechnical properties of the blends, it is found that as the replacement ratio increases, water absorption and LA abrasion linearly increase while CBR decreases exponentially. The predictive equations for water absorption, LA abrasion and CBR are thus proposed in linear and exponential functions of replacement ratio, respectively for the blends with the same particle sizes. To verify the proposed equations, the available test data on RCA-Crushed Brick (CB) and CR-CB blends from Arulrajah et al. (2012) are taken and predicted even though their materials were blended with different grain size distributions.

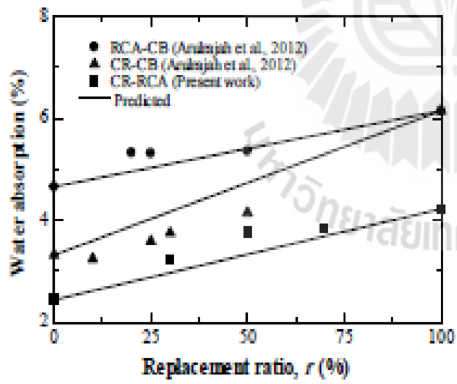

Figure 3. Relationship between water absorption and replacement content.

Figure 3 shows the relationship between water absorption and replacement ratio of RCA-CB blends and CR-CB blends (Arulrajah et al., 2012) and present work (CR-RCA blends). The relationship between water absorption and replacement ratio for CR-RCA blends can be presented as follows:

$$WA_x = a + br_x \tag{1}$$

where WA_x is the water absorption at different replacement ratios, a and b are constants and r_x is the replacement ratio. Constants a and b are approximated from the two physical conditions: WA_x = WA at 0% replacement (WA_0) when r_x = 0% and WA_x = WA at 100% replacement (WA_{100}) when r_x = 100%. As such, a and b are determined from:

$$a = WA_0 \tag{2}$$

$$b = -\left(\frac{WA_0 - WA_{100}}{100}\right) \tag{3}$$

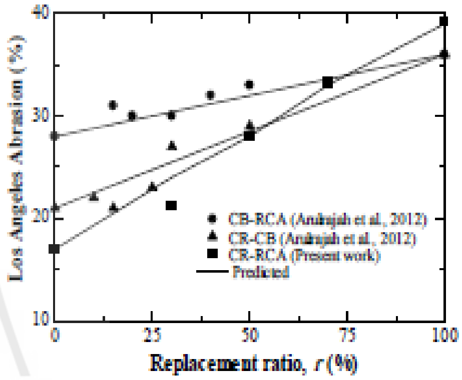

Figure 4. Relationship between LA abrasion and replacement content.

Similarly, the relationship between LA abrasion and replacement ratio is presented as below:

$$LA_x = c + dr_x \tag{4}$$

where LA_x is LA abrasion at different replacement ratios, c and d are constants and determined from

$$c = LA_0 \tag{5}$$

$$d = -\left(\frac{LA_0 - LA_{100}}{100}\right) \tag{6}$$

where LA_0 and LA_{100} are LA abrasion at 0 and 100% replacement ratios, respectively.

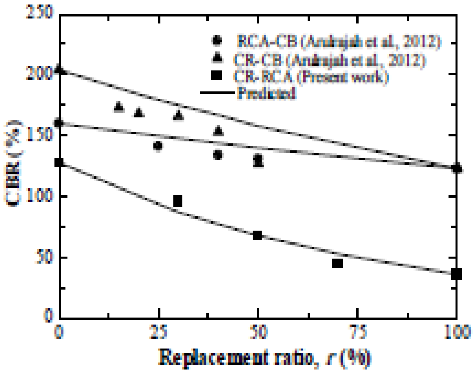

Figure 5. Relationship between CBR and replacement content.

The relationship between CBR and replacement ratio in an exponential function is presented:

$$CBR_x = e\left[\exp(-fr_x)\right] \tag{7}$$

where CBR_x is water absorption at any replacement content. Constants e and f are determined using the following equations:

Table 2. result of comparison between measured and predicted values.

Materials	Replacement ratio (%)	Properties								
		WA (%)			LA (%)			CBR (%)		
		M	P	% error	M	P	% error	M	P	% error
RCA-CB	0	4.66	4.66	0	28	28	0	160	160	0
	15	NA	NA	NA	31	29	6	NA	NA	NA
	20	5.33	4.96	7	30	30	1	NA	NA	NA
	25	5.32	5.03	5	30	30	0	141	150	6
	40	NA	NA	NA	32	31	3	134	144	7
	50	5.36	5.41	1	33	32	3	131	140	7
	100	6.15	6.15	0	36	36	0	123	123	0
CR-CB	0	3.32	3.32	0	21	21	0	204	204	0
	10	3.24	3.6	11	22	23	2	NA	NA	NA
	15	NA	NA	NA	21	23	11	173	189	9
	20	NA	NA	NA	NA	NA	NA	168	184	10
	25	3.59	4.03	12	23	25	8	NA	NA	NA
	30	3.75	4.17	11	27	26	6	166	175	6
	40	NA	NA	NA	NA	NA	NA	153	167	9
	50	4.15	4.74	14	29	29	2	127	158	25
	100	6.15	6.15	0	36	36	0	123	123	0
CR-RCA	0	2.44	2.44	0	17	17	0	128	128	0
	30	3.23	2.97	8	21	24	12	96	87	9
	50	3.76	3.33	11	28	28	1	68	68	0
	70	3.83	3.69	4	33	33	2	45	53	18
	100	4.22	4.22	0	39	39	0	36	36	0
Mean absolute percentage error		5.3			3.0			6.6		

Noted: M = measured and P = predicted

$$e = CBR_0 \tag{8}$$

$$f = -\frac{\ln\left(\frac{CBR_{100}}{CBR_0}\right)}{100} \tag{9}$$

where CBR_0 and CBR_{100} are CBR at 0 and 100% replacement ratios, respectively.

Based on the proposed equations, a and b are 2.4 and, 0.018, 4.7 and 0.015, 3.3 and 0.028 for CR-RCA, RCA-CB and CR-CB blends, respectively; c and d are 17, 0.22, 28 and 0.08, 21 and 0.15 for CR-RCA, RCA-CB and CR-CB blends, respectively and e and f are 127.8, -0.013, 203.8 and -0.005, 160.0 and -0.003 for CR-RCA, RCA-CB and CR-CB blends, respectively. Using the constants a to f, Table 2 shows the prediction of water absorption, LA abrasion and CBR for RCA-CB and CR-CB blends and compared with measured ones. The predicted and measured data are in a good agreement, reinforcing the applicability of the proposed equations. The prediction error is possibly due to the equations being developed from the blends with the same gradation. However, the error is acceptable for engineering practice with mean absolute percent error of less than 5.3%, 3.0% and 6.6% for WA, LA abrasion and CBR, respectively.The mean absolute percent error is

$$\frac{\sum\left|\frac{A_m - A_p}{A_p}\right|}{n}\times 100 \qquad (10)$$

where A_p and A_m are predicted and measured values, respectively and n is the number of data.

5 CONCLUSIONS

The physical and geotechnical properties including that for gradation, specific gravity, compaction, water absorption, LA abrasion and CBR of Crushed Rock and Recycled Concrete Aggregate (CR-RCA) blends are investigated and analyzed in this paper. The gradation of the blends is in accordance with the requirement for base/subbase materials. All physical and geotechnical properties are found to be dependent on replacement ratio. Specific gravity of blends decrease as the RCA content increases due to the low specific gravity of mortar attached on the RCA particles. The Optimum Water Content (OWC) increases while maximum dry density of the blends decreases with increasing RCA content. This might be because the mortar on the RCA particle has lower specific gravity and higher water absorption. The increase in OWC is associated with the increase in water absorption. The LA abrasion value increases linearly with the RCA content due to weakness of mortar attached on the RCA particles. Based on the analysis of the physical and geotechnical properties of the CR-RCA blends, the predictive equations for water absorption, LA abrasion and CBR are proposed in terms of replacement ratio in linear and exponential functions, respectively. The available test data of RCA-CB and CR-RCA blends were taken to validate the proposed equations. The predicted and measured data are in good agreement with low mean absolute percent error. The prediction error is possibly because the equations were proposed based on the CR-RCA blends with the same gradation of CR and RCA. These proposed equations are considered as useful for geotechnical and pavement practitioners for pavement design and selection of pavement materials.

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BIOGRAPHY

Mr. Sereyroath Chea, was born in 1988 in Cambodia. He earned two Bachelor's degrees: one in Finance and Accounting from the National University of Management (NUM) in 2009 and another degree in Engineering from the Institute of Technology of Cambodia (ITC) in 2012. In June 2013, he was awarded a scholarship from the ASEA-UNINET program under the financial support of the government of Austria and Thailand to pursue his Master's degree in Civil Engineering at Suranaree University of Technology (SUT), Thailand. In addition, he was able to complete his research with the financial support of the Thailand Research Fund and the Higher Education Research Promotion and National Research Fund of Thailand, office of Higher Education Commission. During this time, he published an international conference paper. He plans to be able to apply his learning to help further develop Cambodia's construction industry.