



**THESIS APPROVAL**  
**GRADUATE SCHOOL, KASETSART UNIVERSITY**

Master of Engineering (Civil Engineering)

**DEGREE**

Civil Engineering

**FIELD**

Civil Engineering

**DEPARTMENT**

**TITLE:** Reuse of Cracked Concrete Test Cubes in Masonry Structure  
by Using Cement Paste Strengthening

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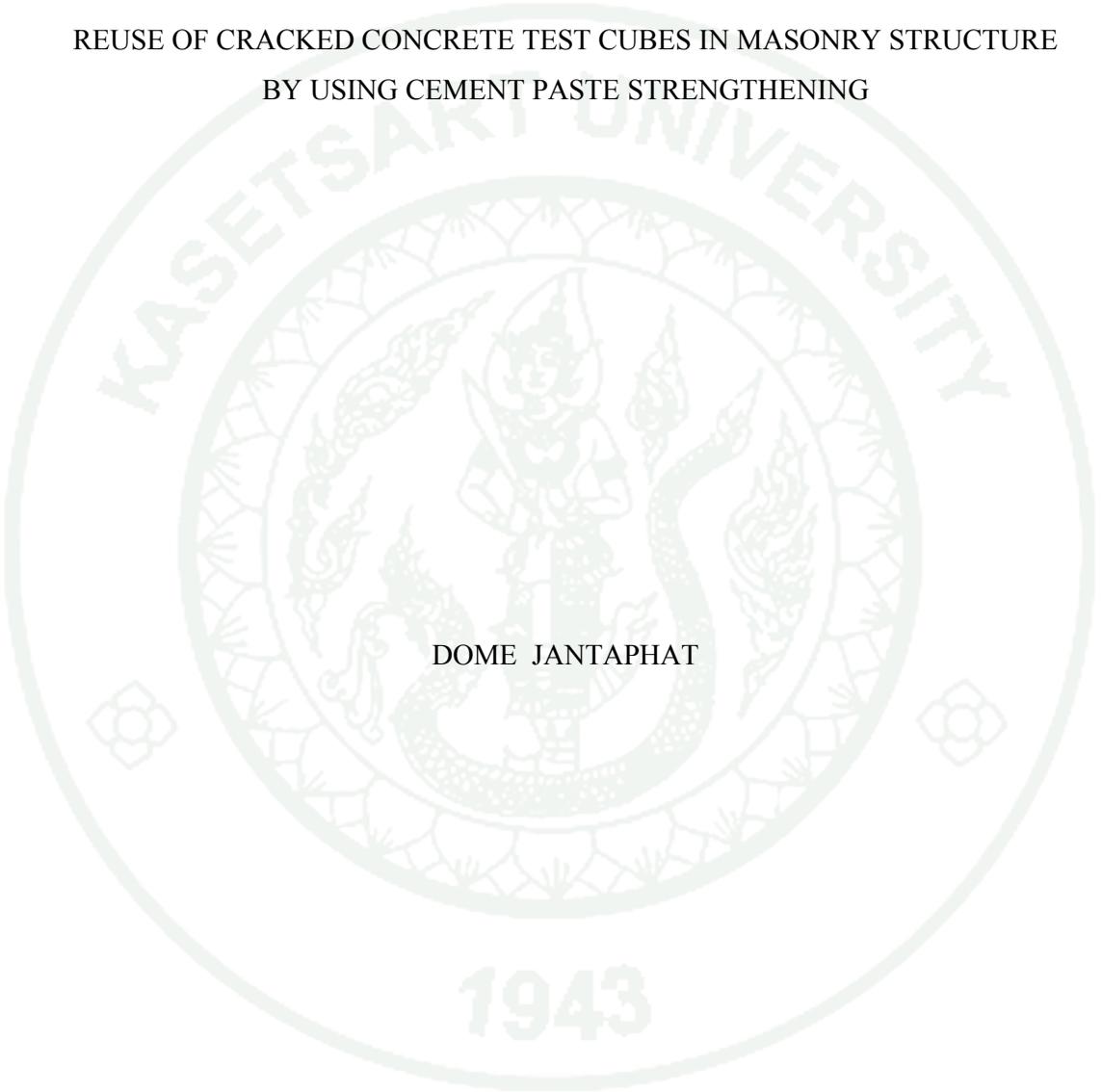
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THESIS

REUSE OF CRACKED CONCRETE TEST CUBES IN MASONRY STRUCTURE  
BY USING CEMENT PASTE STRENGTHENING

The logo of Kasetsart University is a large, light green circular emblem. It features a central figure, likely a deity or a personification of knowledge, surrounded by a decorative border. The text "KASETSART UNIVERSITY" is written in a semi-circle at the top, and "1943" is at the bottom. Two small floral motifs are positioned on the left and right sides of the emblem.

DOME JANTAPHAT

A Thesis Submitted in Partial Fulfillment of  
the Requirements for the Degree of  
Master of Engineering (Civil Engineering)  
Graduate School, Kasetsart University  
2011

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Dome Jantaphat 2011: Reuse of Cracked Concrete Test Cubes in Masonry Structure by Using Cement Paste Strengthening. Master of Engineering (Civil Engineering), Major Field: Civil Engineering, Department of Civil Engineering. Thesis Advisor: Assistant Professor Wanchai Yodsudjai, D.Eng. 109 pages.

The objectives of this research are to determine the optimum water-cement ratio of cement paste in the strengthening of cracked concrete test cubes, to study the use of strengthened cracked cubes as a main element in masonry structure and to compare the cost, weight, strength and aspect of construction of masonry structure constructed by strengthened cracked cubes with other masonry building. All concrete test cubes in the strengthening were derived from testing in laboratory at the highway construction project (Bypass Saraburi, east side, section 1) of the Department of Highways. After concrete test cubes were tested for compressive strength, cracked concrete test cubes at the age of 14 and 28 days were soaked in Portland cement type I paste for 30 minutes and continuously stirred simultaneously. Then they were reshaped by using cement paste from both Portland cement type I and mixed cement for comparison and cured in water for 14 and 28 days. In the part of construction and comparison, one story house is used as the case study.

As a result, it can be concluded that cement paste can be used for strengthening of cracked concrete test cube, and in addition 28 days of curing time in the strengthening gives higher enhancement of the ultimate compressive strength than 14 days of curing time. Also the most appropriate method for the strengthening of cracked concrete test cube at both 14 and 28 days of age is the soaking in 1.25:1 of w/c of cement paste and reshaped by Portland cement. Furthermore, the one story house constructed by concrete cubes is better than that constructed by conventional masonry units in terms of economy and strength capacity. However the factors that are of especial concern are foundations and soil because of weight of concrete cubes.

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## ACKNOWLEDGEMENTS

I would like to extend grateful thanks and am deeply indebted to Asst. Prof. Dr. Wanchai Yodsudjai my thesis advisor, for advice, encouragement and valuable suggestions for the writing of this thesis.

I would like to acknowledge workmen and engineers of the Bypass-Saraburi highway construction project (east side, section 1) of the Department of Highways and collaborators for providing their kind assistance, equipment, labor and laboratory.

I am especially indebted to my parents for their support and cooperation in construction of case study structure.

Dome Jantaphat

April 2011

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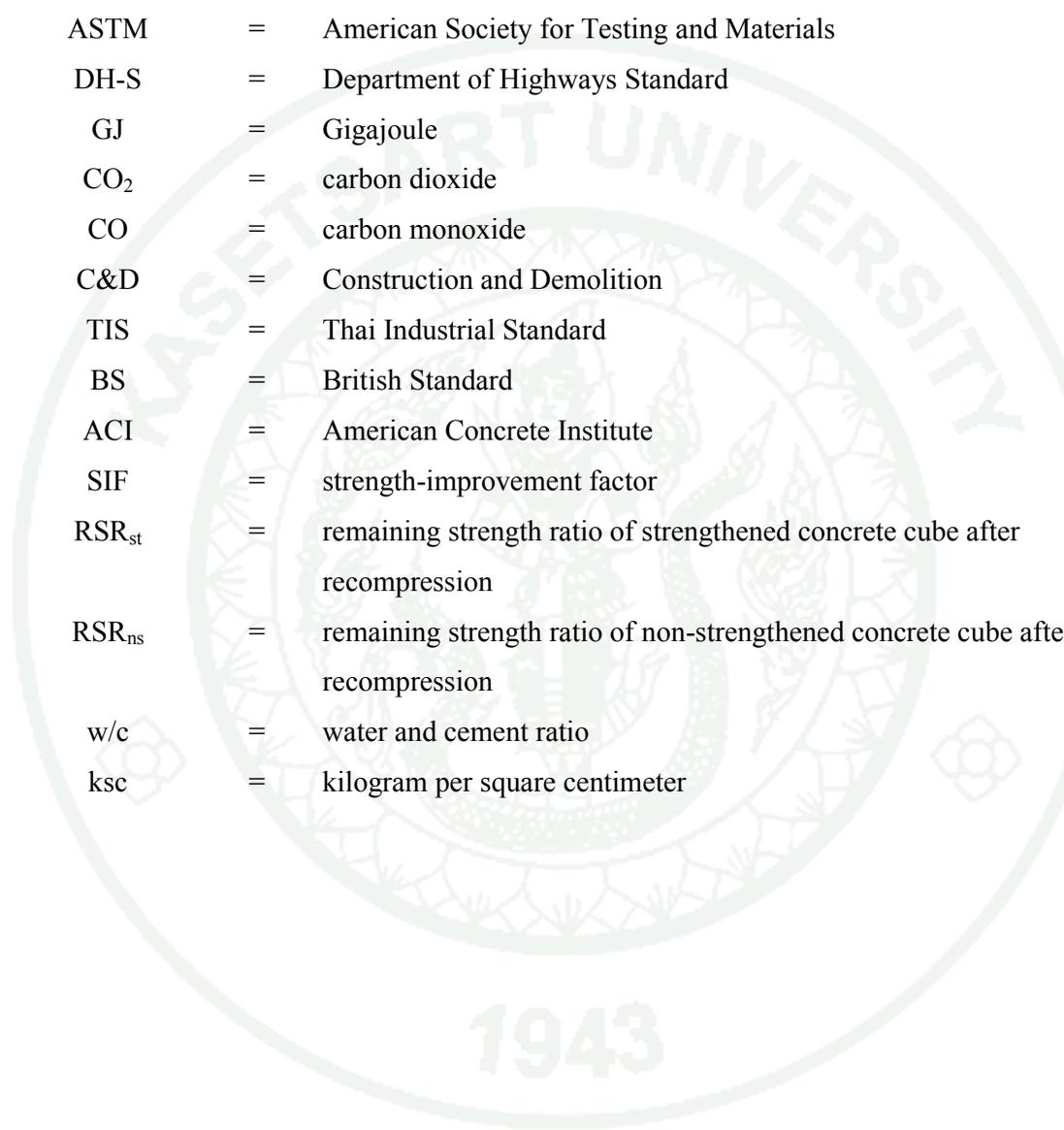
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## LIST OF ABBREVIATIONS



ASTM	=	American Society for Testing and Materials
DH-S	=	Department of Highways Standard
GJ	=	Gigajoule
CO <sub>2</sub>	=	carbon dioxide
CO	=	carbon monoxide
C&D	=	Construction and Demolition
TIS	=	Thai Industrial Standard
BS	=	British Standard
ACI	=	American Concrete Institute
SIF	=	strength-improvement factor
RSR <sub>st</sub>	=	remaining strength ratio of strengthened concrete cube after recompression
RSR <sub>ns</sub>	=	remaining strength ratio of non-strengthened concrete cube after recompression
w/c	=	water and cement ratio
ksc	=	kilogram per square centimeter

# **REUSE OF CRACKED CONCRETE TEST CUBES IN MASONRY STRUCTURE BY USING CEMENT PASTE STRENGTHENING**

## **INTRODUCTION**

In the engineering construction, the testing of material is a must. Compressive strength testing of concrete in construction site especially concrete construction is very significant and necessary to assure that the properties of concrete meet the requirement of the specification. The compression test shows not only the compressive strength of hardened concrete but also the best possible strength of concrete which can be reached in perfect conditions. The testing is done in a laboratory off-site. The only work done on-site is to make concrete specimens for the compression test.

Typically, there are two shapes of concrete specimen in the strength testing, including cube and cylinder. A concrete cube is widely used in the United Kingdom, Germany and almost all countries in Europe (Parinya and Chai, 2008: 175). In these countries, the uniaxial compression test is required to conform to British Standard Specification. In the United States, France, Canada, Australia and New Zealand, a concrete cylinder is used (Parinya and Chai, 2008: 175). The compressive strength of cylindrical concrete specimens is tested in accordance with American Society for Testing and Materials (ASTM) Designation. Nowadays, both cube and cylinder are used for the testing in Thailand. A tester can specify whether to use cube or cylinder strengths for mix design.

In Thailand, the highway construction in part of the Department of Highways is constructed according to DH-S Standard. Standard for Portland cement concrete pavement construction (Department of Highways, 2001) requires a contractor to take one test sample every 50 m<sup>3</sup> of the concrete pouring or one sample in case of placing less than 50 m<sup>3</sup>. Each sample has three concrete cubes for the compression test. The 28 days compressive strength of concrete cube is normally used in design; however, in the practical construction, the 14, 28 and less than 14 days concrete cubes are used in testing. The concrete cubes that have age less than 14 days, called a spare part, are tested in a necessary situation, for example, opened to traffic within 14 days of concrete placing. Therefore, each sampling consists of 9 concrete cubes; as a consequence, there are many concrete specimens for testing in a highway construction which includes not only concrete pavement but also other concrete structures such as foundation and bridge.



**Figure 1** The leftover concrete cubes after project completed.

The residual concrete test specimens after the construction is completed include cracked concrete test specimens and untested concrete specimens. Only untested or very small unseen cracked specimens are selected for use in many purposes, such as, for planting, making fence, building path and parking floor. Meanwhile, cracked concrete specimens are abandoned by disposing in landfills or fill in damaged road.



**Figure 2** Using concrete cube for many purposes in construction site.

Nowadays, the purposes of using cracked concrete test specimens lead to recycling. Specimens are broken into smaller pieces for the further usage such as material in highway construction and aggregate in other concrete constructions. The recycling method that is processed by machine causes an investable issue, pollution and waste of energy. The energy and environmental problem should be topics of concern due to the global warming situation at the present time. For these reason, the method of reusing concrete specimen without consuming energy and environmental impact is an excellent practice. Moreover, it will be an advantage for individuals who use concrete specimen in building or other purposes without capital for recycling.



**Figure 3** The problems from using concrete cube by recycling and in landfill.

The objective of this research is to study the method for strengthening the cracked concrete test cube. As this study needs the easiest method for the strengthening, cement paste is a suitable material. The soaking of cracked concrete cube in cement paste produces a process of percolation of cement paste through cracks that happen inside concrete cube; accordingly, the cracked concrete cube is strengthened.

Moreover, this research studies the use of strengthened concrete cubes as a main element in masonry structure. The comparison of structural cost, weight, strength and the aspect of construction of masonry structure constructed by the concrete cubes with other masonry materials are also performed

## OBJECTIVES

1. To strengthen the cracked concrete test cubes by the technique of soaking in cement paste.
2. To apply the strengthened cracked concrete test cubes in the masonry structure.
3. To compare the economic, structural and constructive aspects of concrete cube with other masonry units in masonry structure.

## Scope of Research

1. This research addresses only cube shape of specimen which is commonly used for determining concrete compressive strength in the highway construction project in Thailand.
2. The experiment is separated into three parts; the strengthening of cracked concrete test cube, the comparison with other masonry unit, and the application of reusing (case study).
3. The strengthening part is divided into two tasks; the non-strengthened cube testing and the strengthened cube testing.

4. All of the tested cubes in strengthening part are derived from the Bypass-Saraburi highway construction project (east side, section 1) of the Department of Highways.

5. The method of strengthening is only the soaking in cement paste.

6. The condition in time of soaking in cement paste will not be taken into consideration and analysis.

7. Materials used in the process of reshape after the strengthening of cracked cube in cement paste are Portland cement type I paste and mixed cement paste.

8. The concrete cubes tested in the strengthening part of this research include the cubes at the age of 14 and 28 days.

9. The times of curing after strengthening in cement paste are 14 and 28 days.

10. The masonry units which are used in the comparison with the concrete cube include brick, concrete masonry unit and lightweight concrete block.

11. One story building with 4x6 meters and a height of 3 meters using masonry unit as main component of structure and supported by strip footing is used as the case study.

12. In the part of the comparison, this research focuses primarily on the economics, weight aspects and construction aspect. Other aspects, such as durability, transportation of material, strength of the building, are not covered in this study.

13. This study does not consider the brand of cement and the manufacturer of masonry unit.

14. Advantage of concrete cube reused to use as masonry unit in construction primarily focuses on local people nearby construction site.

## LITERATURE REVIEW

### 1. Impact of Concrete on the Environment

Concrete is used as building material worldwide because of a number of advantages. If properly designed, it has excellent properties and durability. Concrete is an engineered material, which means that mixes can be designed to satisfy any set of performance specifications. Concrete is the most widely used as construction material for new and replacement infrastructure needs in the world especially in the Asian region. According to Gjørsvik and Sakai (2000), the concrete production in the world is expected to rise from about 10 billion tons in 1995 to almost 16 billion tons in 2010. Unfortunately, the concrete industry is one of the largest consumers of natural resources and energy, and is responsible for large emissions of carbon dioxide. Mayer (2004) revealed an enormous impact of the concrete industry on the environment as follows:

1) Worldwide, over ten billion tons of concrete are being produced each year. In the United States, the annual production of over 500 million tons implies about two tons for each man, woman and child. Such volumes require vast amounts of natural resources for aggregate and cement production.

2) The production of one ton of Portland cement causes the release of one ton of CO<sub>2</sub> into the atmosphere. CO<sub>2</sub> is known to be a greenhouse gas that contributes to global warming, and the cement industry alone generates worldwide about 7% of it.

3) The production of Portland cement is also very energy-intensive. Although the North American plants have improved their energy-efficiency considerably in recent decades to the point where it is now comparable to that of plants in Japan and Germany, it is technically next to impossible to increase that energy efficiency much further below the current requirement of about 4 GJ per ton.

4) The demolition and disposal of concrete structures, pavements, etc., constitutes another environmental burden. Construction debris contributes a large fraction of our solid waste disposal problem, and concrete constitutes the largest single component.

5) Finally, the water requirements are enormous and particularly burdensome in those regions of the earth that are not blessed with an abundance of fresh water. The concrete industry uses over 1 trillion gallons of water each year worldwide, and this does not even include wash water and curing water.

Moreover, Struble and Godfrey (2004) gave attention to the environmental impact of each separate constituent of concrete as follows:

The aggregates are usually obtained by mining. The coarse and fine aggregates are usually mined separately. Occasionally aggregate is obtained as a by-product of some other process (e.g., slag or recycled concrete). Aggregates may be crushed and may be washed. They are usually separated into various size fractions and reconstituted so as to satisfy the grading requirements. They may need to be dried. A modest amount of energy is involved in all these processes. The principal wastes are

dust and water, neither of which is especially damaging to the environment. The dust may be used in some other process or may be disposed of in a landfill.

The hydraulic cement may be straight Portland cement or a mixture of Portland cement and some proportion of a supplemental cementing material such as fly ash or slag. Portland cement is usually manufactured by heating a mixture of limestone and shale in a kiln to a high temperature (approximately 1500°C), and then clinker is mixed with gypsum to form a fine powder. Thus it is not surprising that the Portland cement has a rather high embodied energy. The reaction between limestone and shale to produce clinker produces CO<sub>2</sub>. Furthermore, the fuel used in the kiln and the electricity in the grinding mills themselves produces some amount of gaseous waste, principally CO<sub>2</sub> and CO. These gases are non-toxic and are released to the atmosphere, where they contribute to global warming.

The water in concrete is normally ordinary tap water with no further processing. Thus it has very little embodied energy and no waste. It is only an environmental issue in locations where the water is already not sufficient for basic needs.

Concrete is usually manufactured by combining and mixing these constituents in large batches in a ready-mixed concrete plant and hauling the mixture to the construction site in a truck. These processes (moving materials, mixing them, and hauling the concrete) require modest amounts of energy and produce small amounts of waste. Dust, unused concrete, and wash water contaminated with concrete are the principal waste, and the latter two wastes may be at least partially reclaimed and

reused. The environmental impact of using concrete at a construction site is basically similar to the impact of manufacturing concrete in a ready-mixed concrete plant (Struble and Godfrey, 2004). The concrete is moved to its desired location, consolidated into the formwork, and finished. Waste includes unused concrete, contaminated wash water, and used formwork. During the lifetime of the structure, the impact of concrete on environment is primarily a function of its role in energy transmittance (i.e., its insulating properties) and its role in energy storage (Struble and Godfrey, 2004). At the end of its service life, a concrete structure must be demolished and disposed of. These facts seem to indicate that the concrete industry has become a victim of its own success.

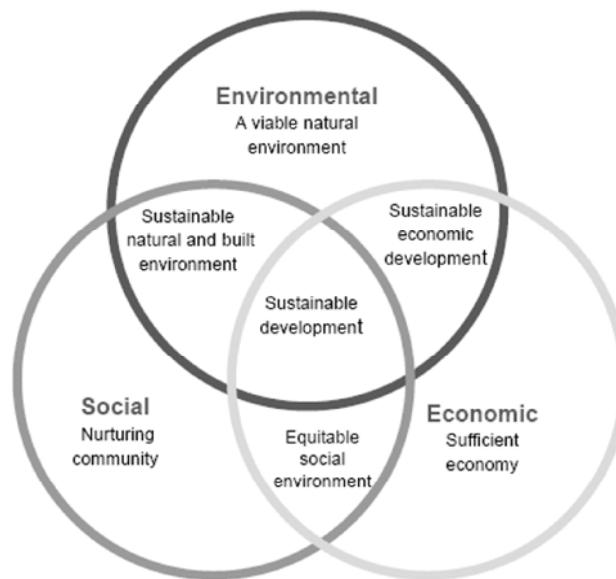
In many countries, the construction industries are trying to reuse and decrease concrete or solid waste material on construction sites. The utilization of solid waste is the challenge for the civil and environmental engineers to utilize economic friendly materials produced at reasonable cost with the low possible environmental impact. Therefore, the reuse of cracked concrete test cube in this research is studied to decrease solid waste on construction sites.

## **2. Concrete in Sustainable Development**

Technical performance and ecological responsibility have come closer to each other in the consciousness of society. Engineering performances are analyzed and evaluated not only on the basis of technical specifications, but also on the background of the effect on the environment. The goals are set to conserve natural resources and minimize waste quantity, as well as the reduction of further environmental effects.

Engineers should give serious consideration to sustainable construction materials and practices. Sustainable building practices are the wave of the future. Nowadays, the demand for eco-friendly building practices is high. Green concrete (Damtoft et al., 2001) is an example of concrete structure with reduced environmental impact in terms of reduced energy consumption, reduced emissions to the atmosphere, reduced waste water and reduced consumption of natural resources. Going green is not as simple as using a few green products in homes that are built. Look at the entire project. Integrate the various sustainable options to provide a full green package. This is the best way to earn reputation as a green builder (Woodson, 2009).

Sustainable development encompasses three general elements: environment, economic and social responsibility. These elements can be shown diagrammatically as Figure 1. At the moment, the environment is probably the most important component, and an engineer or architect uses sustainability to mean having no net negative impact on the environment. Thus the term sustainable has come to be synonymous with environmentally sound or friendly and “green” (Struble and Godfrey, 2004).



**Figure 4** The principle of sustainable development.

**Source:** CIRIA (2009)

The environmental component is classified as the first component because deterioration of environment is driving the current worldwide focus on sustainable development. Probably the most troubling for the long-term health of the planet and for the goal of sustainability are the climate changes resulting from the thinning of the ozone layer and the progressive decline in biodiversity resulting from loss of habitat. Both of these changes are a direct result of human development. (Struble and Godfrey, 2004)

The economic component is given less attention in the developed countries of the world, but is equally essential to the goal of sustainable development. There is

poverty throughout the planet, and the global inequities in consumption of resources are staggering. Large amounts of money are spent hauling, transporting and disposing of waste, funds that could be used more efficiently in other activities; the generation of waste therefore involves a poor utilization of public funds (Munier, 2005).

The social component is also given less attention at the moment but will hopefully be brought into balance in the ensuing decades (Struble and Godfrey, 2004). Waste is a health hazard especially in developing countries. As for industrial waste, there is the deterioration of public health when one considers acid and alkaline discharges, particulates and other pollutants that contaminate the air, soil, and water. (Munier, 2005)

In a world increasingly fixated on the demands of sustainable development, the industry's basic challenge is therefore to fully exploit the advantages of concrete, while relying less on Portland cement. There are four basic categories of tools and strategies to achieve this goal (Meyer, 2006):

- 1) Increased reliance on recycled materials. Since aggregate constitutes the bulk of concrete, the most effective recycling strategy will have to incorporate the substitution of recycled for virgin materials.

- 2) Improved durability. By doubling the service life of structures, engineer can cut in half the amounts of materials needed for their replacement.

3) Improved mechanical properties. An increase in mechanical strength and similar properties leads to a reduction of materials needed. For example, doubling the concrete strength for strength-controlled members cuts the required amount of material in half.

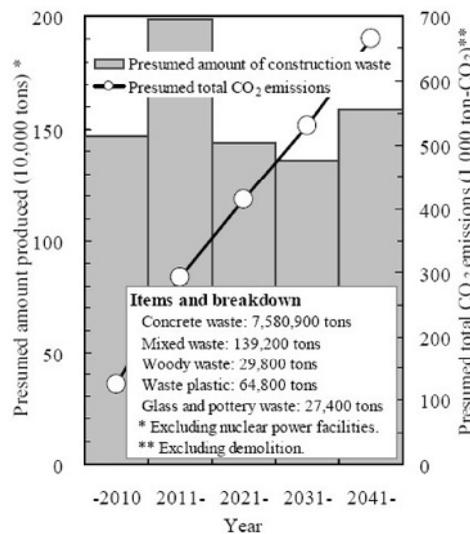
4) Increased use of supplementary cementitious material. Since the production of Portland cement is energy intensive and responsible for CO<sub>2</sub> generation, the increased use of other materials, especially those that are byproducts of industrial processes, such as fly ash and slag, is bound to have a major positive impact. The use of supplementary cementitious material can improve various properties in fresh and hardened state of concrete; however, it also increases the cost of construction. It is now a global concern to make economic friendly material product at lower cost with less harmful effect on environment (Badur and Chaudhary, 2008).

5) Reuse of wash water. The recycling of wash water is readily achieved in practice and already required by law in some countries.

Otherwise, Liu and Chern (2008) expressed that research and use of emerging technologies, development and use of performance-based specifications and codes, and use life-cycle cost approach by seeking better and durable concrete structure rather than lower initial cost, lead to sustainable development of concrete industry.

### 3. Recycling and Reuse of Construction and Demolition Waste

According to an investigation of the Ministry of Land, Infrastructure and Transport in 2002 (Dosho, 2007), the amount of construction waste produced in Japan is approximately 83 million tons per year. Concrete waste accounts for approximately 35 million tons per year. Figure 5 shows the breakdown and amount of construction waste that will be produced when 5,800 buildings of Tokyo Electric Power Company (TEPCO) are demolished. The total predicted amount of construction waste is about 7.8 million tons of which 7.6 million tons is concrete waste. If the total amount of construction waste is treated through dumping in disposal facilities, the amount of CO<sub>2</sub> emissions is predicted to be about 0.67 million tons.



**Figure 5** Presumed amount of construction waste and CO<sub>2</sub> emissions (Buildings owned by TEPCO).

**Source:** Dosho (2007)

To reduce CO<sub>2</sub> emission and avoid construction waste, the multiple use of a material is represented. In recent years, utilizing construction and demolition (C&D) waste for new construction through recycling and reuse has received increased attention throughout the world, especially in the European countries, Japan, the United States, and Taiwan (Liu and Chern, 2008). Construction wastes like concrete, metal, wood, paper and plastic are sorted and recycled to minimize wastage and disposal at the landfill. Concrete wastes like concrete cubes and hardened spillage from trucks are crushed and used for backfilling works. Also the stone boulders from the excavated materials are salvaged and used as landscape features (Govindasamy, 2008). Practical and economic experiences from Japan and Denmark suggest that road base and sub-base materials are expected to be the most important area of use of C&D waste (Liu and Chern, 2008). At present, more than 95% of C&D waste is being recycled and used mainly as road base material in Japan (Kasai, 2004). When used for such purposes, C&D waste (primarily of broken concrete, bricks, and stone) can substitute for up to 20% of the consumption of natural sand, gravel, and crushed stone, thereby saving natural resources (Hansen and Lauritzen, 2004).

Although concrete waste is presently used almost entirely for roadbed gravel, the demand for roadbed gravel is not expected to increase largely due to a decrease in new road construction in the developed countries. In addition, toxic substances such as hexavalent-chromium and lead in the concrete waste cause contaminated soil (Dosho, 2007); therefore, it is necessary to develop other uses apart from roadbed gravel.

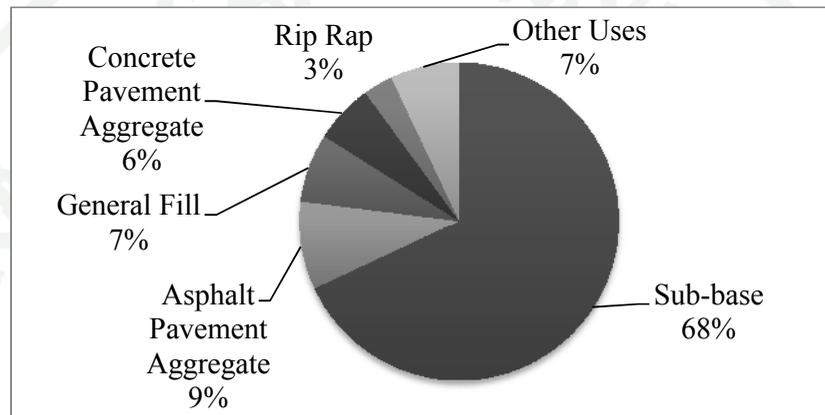


**Figure 6** Recycled aggregate in the industry.

**Source:** CAPPAGH (2006)

Dosho (2007) informed that the most promising alternatives are recycled aggregate, as shown in Figure 6, and recycled aggregate concrete. Recycled concrete has been used as partial replacement of coarse aggregate for the concrete structures and concrete pavements. For example, 35% of the coarse aggregate was replaced with recycled concrete aggregate for the cast in-place concrete for all foundations and 50% of the basement walls and columns in a new high school outside Oslo (Anonymous, 2003). In Singapore, recycled concrete aggregate can be used as non-structural precast concrete components such as road kerbs and drains (Yong and Pin, 2008). At Bay Education Center-Rhode Island in the United States, salvaged waste concrete slabs from the site were reused as crushed concrete structure fill in the building's

foundation and in reconstruction of the revetment sea wall (Moskow, 2008). In the United States, recycled concrete aggregates have been primarily used as fill or sub-base materials as shown in Figure 7.



**Figure 7** Percent of uses of recycled concrete aggregate in the United States.

**Source:** The U.S. Army Corps of Engineers (2004)

Although recycled concrete aggregate has been successfully used as road base, fill material and aggregate in new concrete, a significant amount of C&D waste is still disposed of in landfills. However, the future outlook for recycling concrete is favorable because the local natural aggregate sources and the suitable landfill sites for waste are becoming scarce. Additionally, in the case of manufacturing such recycled aggregate, the manufacturing cost and amount of CO<sub>2</sub> emissions is likely to rise sharply, consequently limiting the extent to which recycled aggregate concrete is used (Dosho, 2007). The reuse of concrete waste after construction, such as concrete test cube that is considered in this research, is a further method.

## MATERIALS AND METHODS

### Materials

1. Portland cement type I following Thai Industrial Standard (TIS) 15
2. Mixed cement following TIS 80
3. Concrete cubes (untested and tested specimens) as shown in Figure 8.



**Figure 8** The untested and tested concrete cube at the construction site.

4. Sand and water conform to the specification for highway construction of the Department of Highways
5. Compressive strength testing machine
6. Dial gauge



**Figure 9** The compressive strength testing machine and dial gauge in the experiment.

7. Concrete cube mold (50 mm x 50 mm x 50 mm)
8. Weighting scale
9. Plastic basin
10. Slump testing apparatus
11. Regular equipment for concrete work

### Methods

To achieve the goals of this research, the experiment is divided into three following parts:

Part I is the determination of the most effective mix design of cement paste in the strengthening of cracked concrete test cube and the study into the difference between the strengthened and the non-strengthened concrete cube.

Part II is the construction by using both the strengthened concrete cubes and untested concrete cubes as a structural material in a masonry structure.

Part III is the comparison between structure constructed by concrete cubes and other masonry units.

## 1. Experimental Preparation

### 1.1 Part I (Strengthening of cracked concrete test cube)

All cubes are derived from testing in the Bypass-Saraburi (east side, section 1) highway construction project. Since the study finds out about the difference between strengthened and non-strengthened concrete cube, the Concrete cubes are divided into 2 groups as shown in Table 1 and Table 3.

**Table 1** Classification of concrete test cubes (Non-strengthened case).

Case	No. of mix	No. of slump each mix	No. of specimen each slump	Ages of tested cube (days)	Total examples
Non-soak	3	2	3	14, 28	36

In case of non-strengthened testing, all of the concrete mixes are derived from the mix design specification of the construction project as shown in Table 2.

**Table 2** Mix proportions of concrete in case of non-strengthened cubes.

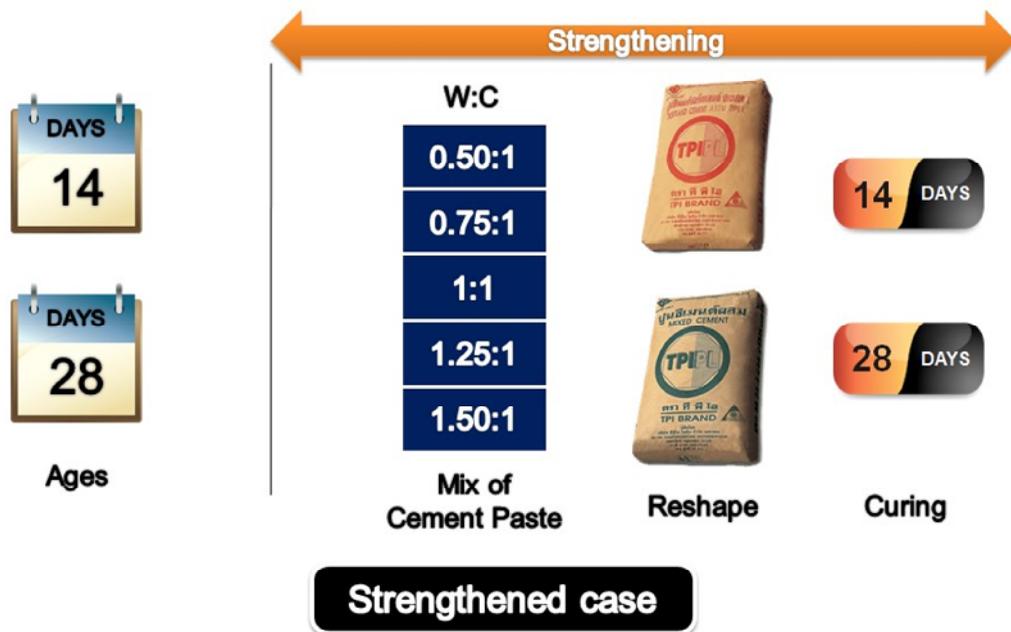
Mix No.	Mix proportion (kg/m <sup>3</sup> )			Slump (cm)
	Cement	Fine aggregates	Coarse aggregates	
1	350	780	1130	8.5
				7.5
2	350	744	1072	7
				9
3	350	709	1184	6
				6.5

**Figure 10** Classification of concrete test cubes (Non-strengthened case).

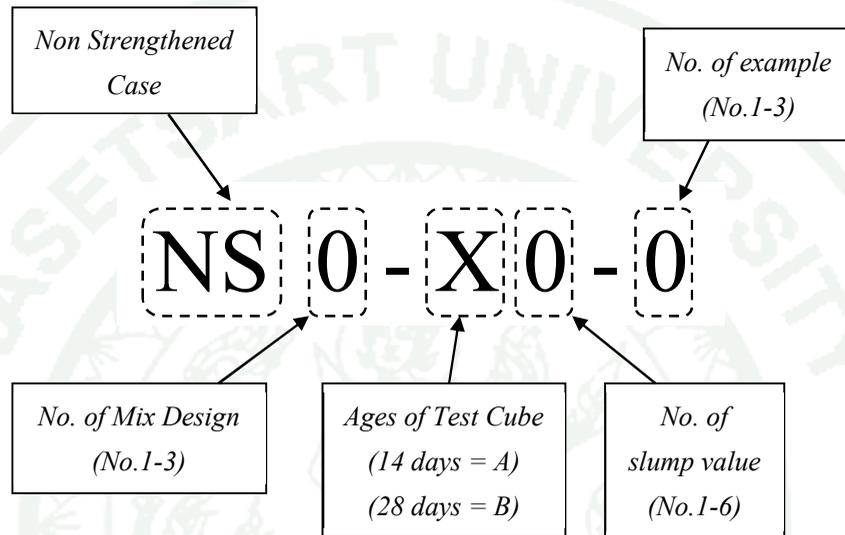
**Table 3** Classification of concrete test cubes (Strengthened case).

Case	No. of cement paste mix	No. of specimen each mix	No. of cement type for reshape	Ages of tested cube (days)	Curing time (days)	Total examples
Soak	5	24	2	14, 28	14, 28	480

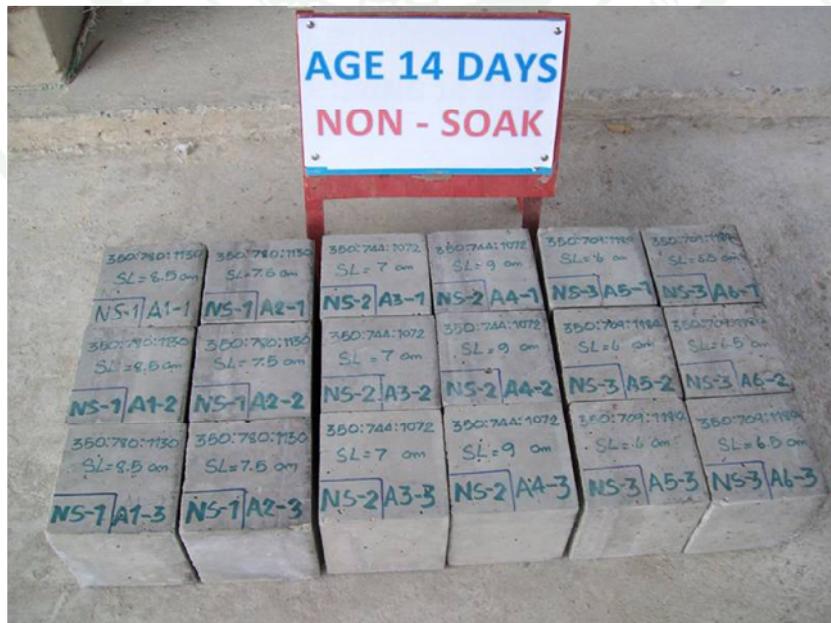
In the process of strengthening, there are 5 mixes of cement paste varying by water-cement ratio; such as, 0.5:1, 0.75:1, 1:1, 1.25:1 and 1.50:1. In the reshape, Portland cement type I paste and mixed cement paste are used.

**Figure 11** Classification of concrete test cubes (Strengthened case).

For convenience, codes are used in testing as shown in Figure 12 and Figure 14.



**Figure 12** Codes used in non-strengthened testing.



**Figure 13** Appearance of concrete cubes in non-strengthened testing.

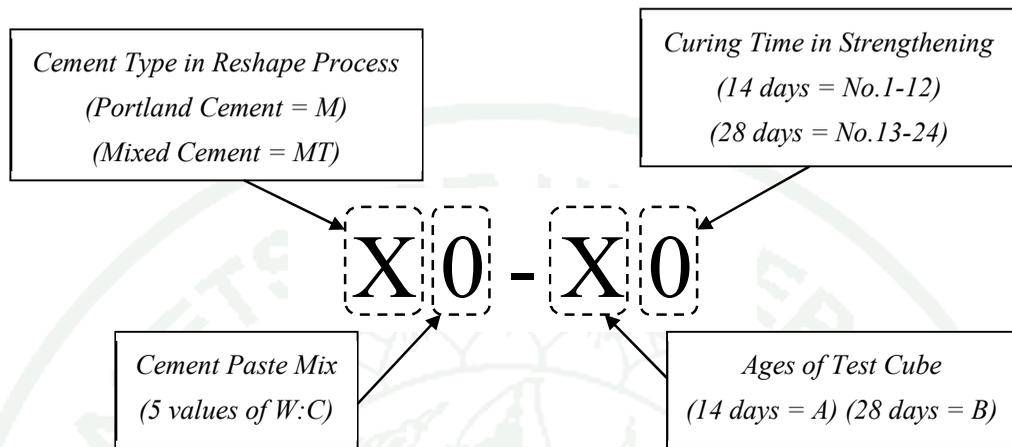


Figure 14 Codes used in strengthened testing.



Figure 15 Appearance of concrete cubes in strengthened testing.

## 1.2 Part II (Application and case study)

Because in highway construction, there are both tested and untested concrete cubes, the structure is constructed from strengthened cracked cube and uncracked cube. All of the concrete cubes are derived from the remainder from many highway construction projects. One-story building is constructed as a case study by using concrete cubes as material in masonry structure.

## 1.3 Part III (A comparison with other masonry units)

One-story building from part II will be used as case study. Brick, concrete masonry unit and lightweight concrete block (now referred to as autoclaved aerated concrete) are compared with concrete cube in terms of the economics, weight, strength, and constructive considerations.

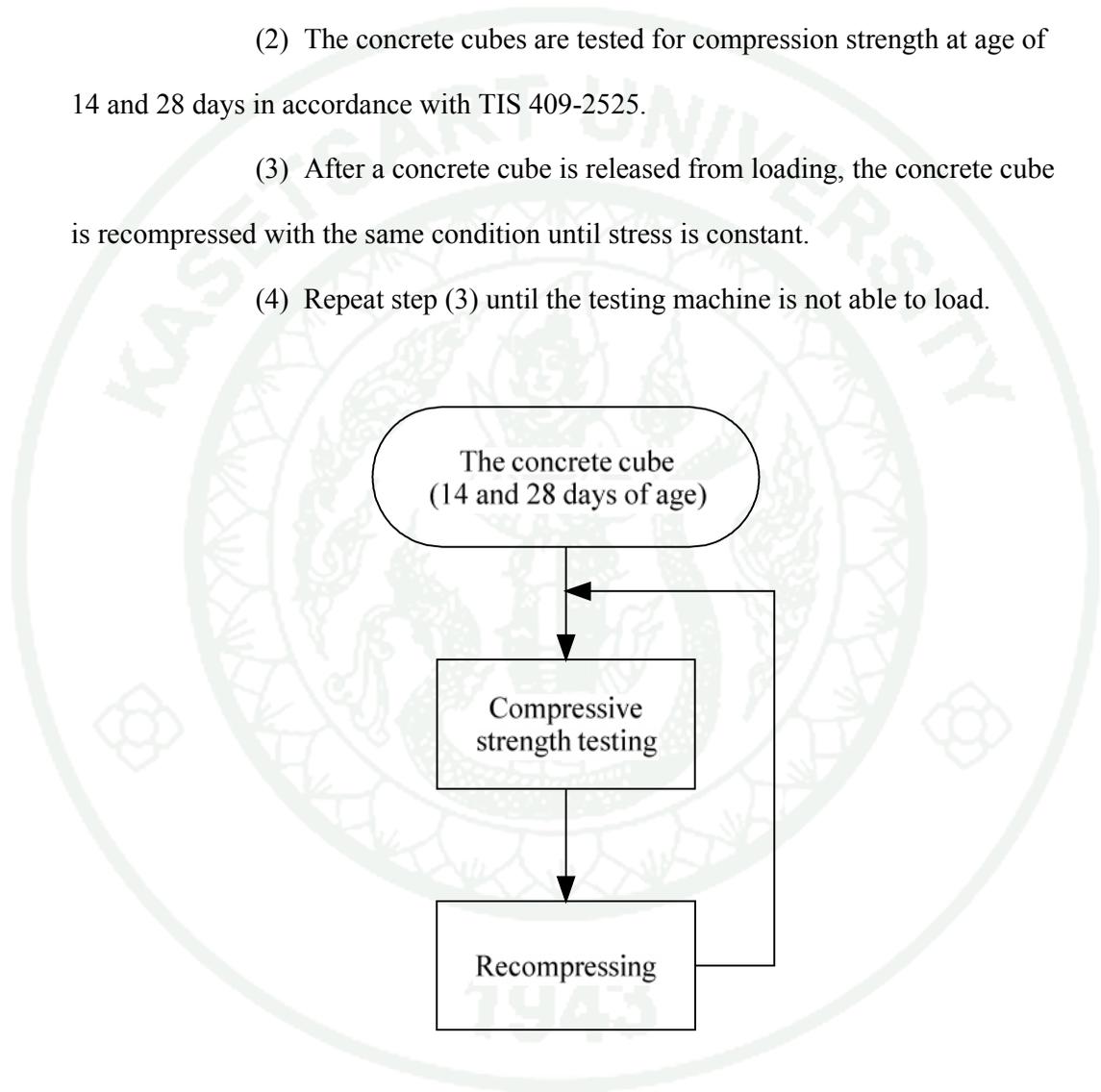
## 2. Testing and Data Collection

### 2.1 Part I (Strengthening of cracked concrete test cube)

#### a) Non-strengthened case

This case is the testing of concrete specimen after it is compressed by strength-testing without the process of strengthening in cement paste. A continuous compression is used for studying the remaining strength of concrete specimen from stress/strain diagram.

- (1) The concrete cubes are cast and cured in accordance with DH-S 303/2532.
- (2) The concrete cubes are tested for compression strength at age of 14 and 28 days in accordance with TIS 409-2525.
- (3) After a concrete cube is released from loading, the concrete cube is recompressed with the same condition until stress is constant.
- (4) Repeat step (3) until the testing machine is not able to load.

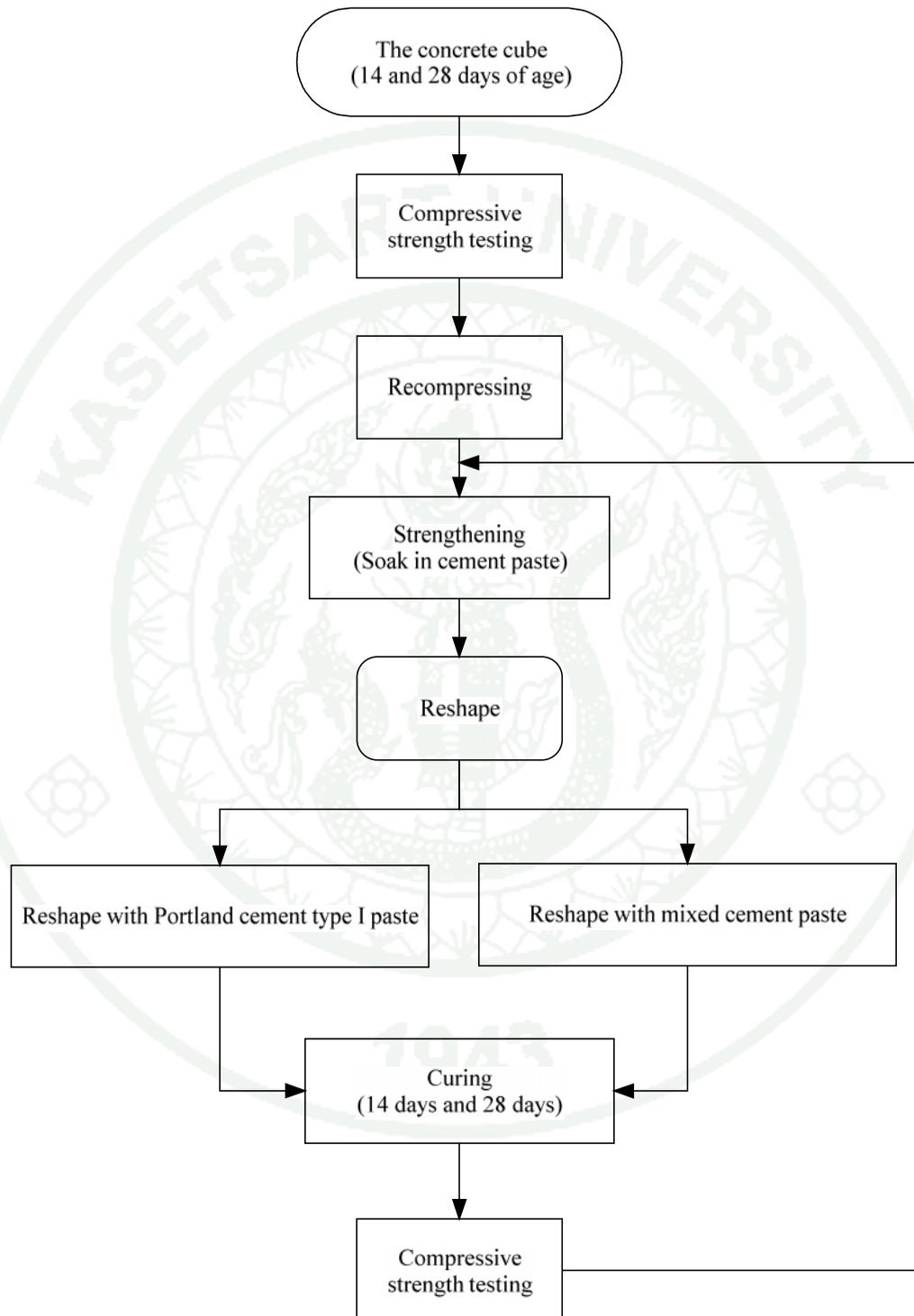


**Figure 16** Procedure of non-strengthened case.

b) Strengthened case

This case is the testing to study an influence of cement paste on the compressive strength of cracked concrete cube soaked in cement paste and to determine the optimum water-cement ratio of cement paste for the strengthening.

- (1) The cracked concrete test cubes are acquired from the compressive testing of the Bypass-Saraburi highway construction project.
- (2) The concrete cubes from previous step are recompressed in accordance with TIS 409-2525. The stress-strain curve obtained from this process is used as reference in the comparison with the concrete cube after strengthening.
- (3) The weight of the concrete cube is measured.
- (4) The concrete cubes from previous step are soaked in cement paste as shown in Figure 13.
- (5) Cement paste is stirred continuously for 30 minutes to prevent setting of mix. After 15 minutes passed, the concrete cubes are turned upside down.
- (6) The concrete cube is removed from the soaking facility and the surface of cube cleaned.
- (7) The weight of the strengthened concrete cube is measured again.
- (8) The strengthened specimens are divided into two groups. The first group of concrete cubes is reshaped by Portland cement type I paste. The second group is reformed by mixed cement paste. The reshape method is shown in Figure 19.
- (9) The specimens are cured in water for 14 and 28 days.
- (10) The specimens are tested as shown in Figure 20 to determine 14, 28-days compressive strength values following TIS 409-2525.



**Figure 17** Procedure of strengthened case.

(11) The stress-strain curves from step (10) are compared with step (2).

(12) Repeat step (3) to (10).

(13) The result of this part is compared with the non-strengthened case to determine the optimum water-cement ratio of cement paste for the strengthening.

(14) The most effective mix of cement paste for strengthening is determined.

(15) The experiment is summarized.



**Figure 18** Soaking of cracked concrete cube in cement paste.



**Figure 19** Reshape of strengthened cracked concrete cube after soaking in cement paste.

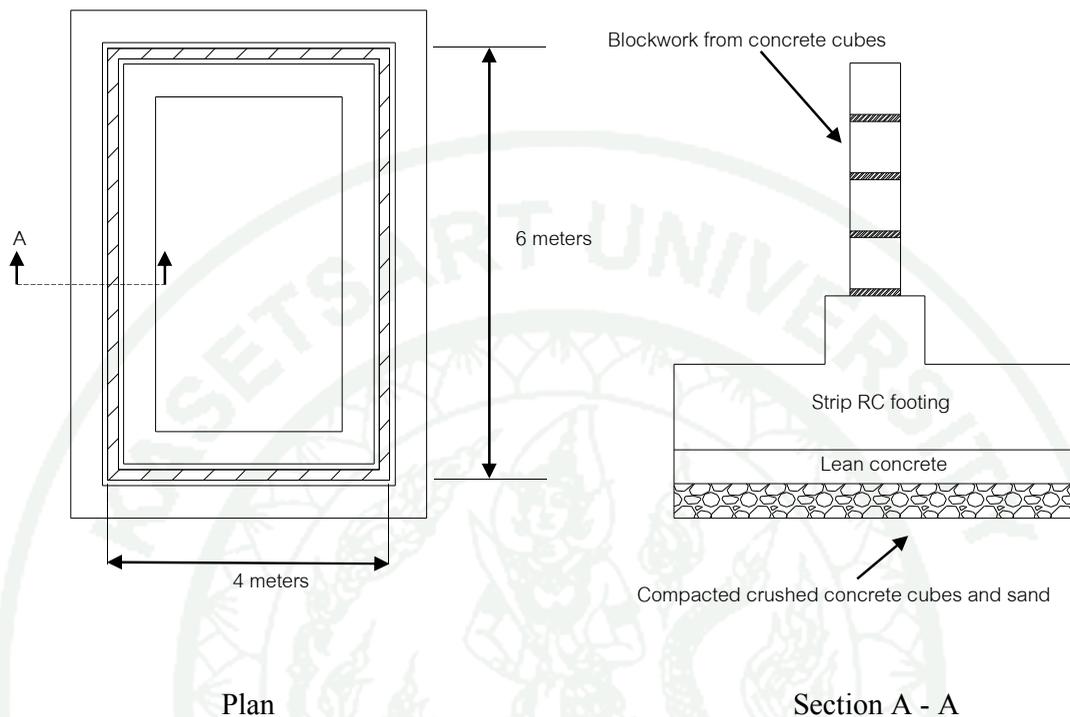


**Figure 20** Compressive strength experiment setup.

## 2.2 Part II (Application and case study)

- a) One-story building is designed and calculated.
- b) Both the cracked and uncracked concrete test cubes are obtained and collected from many highway construction projects.
- c) The cracked concrete cubes are soaked in cement paste for 30 minutes. Mix is obtained from the result in part I. Simultaneously, cement paste is stirred continuously.
- d) The strengthened concrete cubes are cured in water. Time of curing depends on the result from part I.
- e) One-story building is constructed by using concrete cube as loaded wall in masonry structure.
- f) The result is discussed in aspect of construction.
- g) The experiment is summarized.

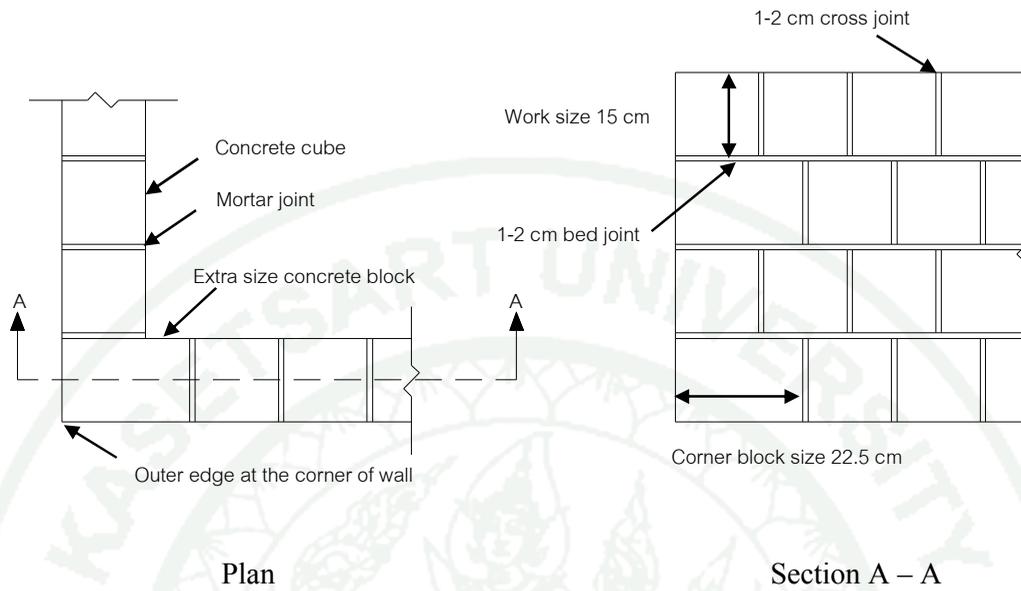
In the construction part, one-story house (4x6 meters and a height of 3 meters from the top of footing) wall supported by strip footing as shown in Figure 21 is constructed of both untested concrete cubes and strengthened concrete cubes. Additionally, the broken concrete cubes, which are not able to be strengthened, are compacted and filled in the house's foundation base for improvement of soil below footing and leveling.



**Figure 21** The masonry structure of one-story house constructed as the case study.

This unreinforced masonry structure is designed by considering in the recommendations given in BS 5628 (Code of Practice for Use of Masonry) and ACI 530-05 (Building code Requirements for Masonry Structures). Nevertheless, due to the fact that the concrete cube is not classified into groups of masonry unit, this research is not able to use only the code of practice or code requirements in the construction without experiment on prior work.

Because stretcher bond is used in block laying, the masonry units at the corner, which is cast separately, require the block size to be equal to 1.5 of the cube length to use at the wall end as shown in Figure 22.



**Figure 22** The layout, work size and joint of masonry wall.

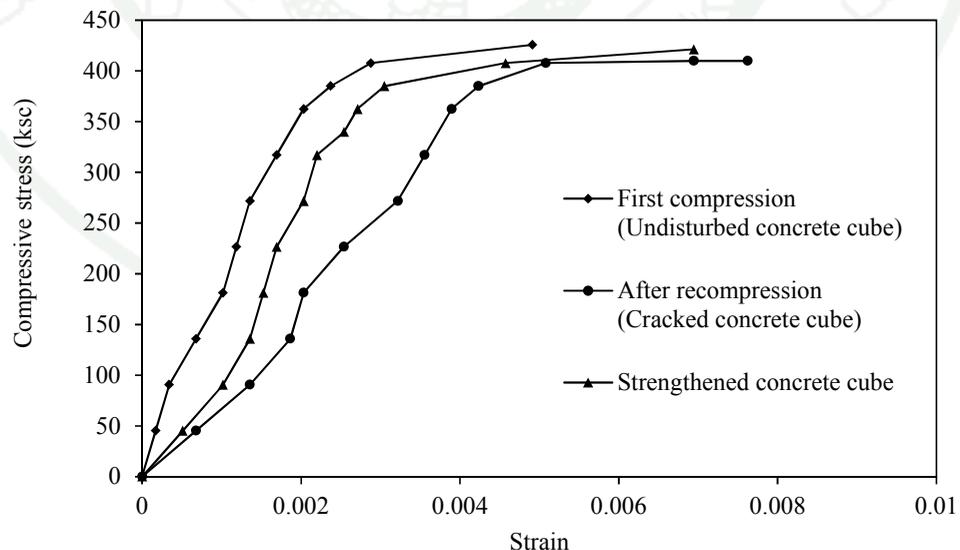
### 2.3 Part III (A comparison with other masonry units)

The testing in part I and construction in part II are analyzed to compare the economic, structural and constructive aspects of concrete cube with other masonry units in masonry structure.

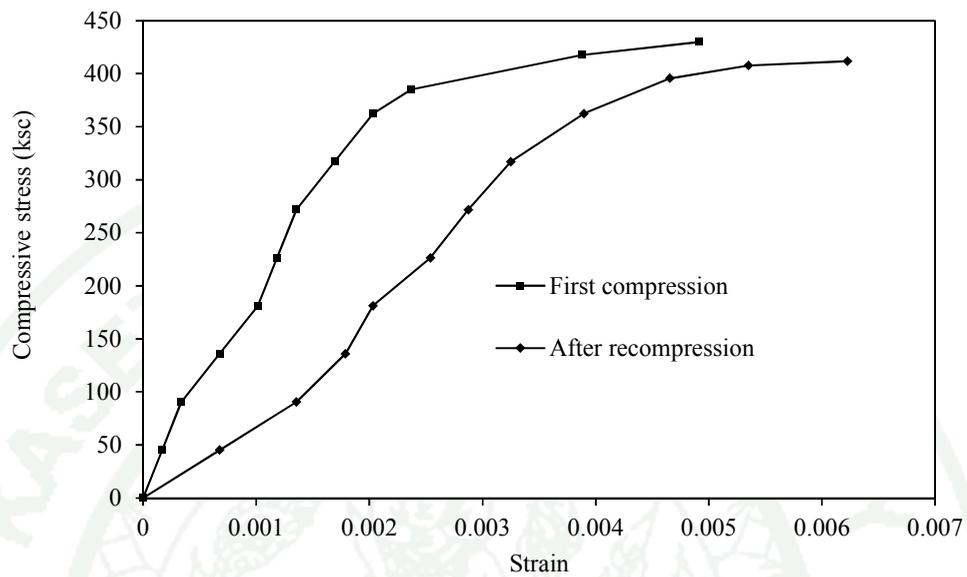
## RESULTS AND DISCUSSION

### 1. Strengthening of Cracked Concrete Test Cube

The stress-strain curves in case of strengthened and non-strengthened concrete cubes reveal the difference between the two cases. In the result of strengthened concrete cubes reshaped by Portland cement paste, there is an increase of ultimate compressive strength and elastic modulus as shown in Figure 23. However, in the non-strengthened case and strengthened case with reshape with mixed cement paste, there is no improvement in ultimate strength and elastic modulus. The example of the stress-strain curve from testing in case of non-strengthened concrete cube is shown in Figure 19.



**Figure 23** The stress-strain relationship in case of strengthened concrete cube reshaped by Portland cement paste.



**Figure 24** The stress-strain relationship in case of non-strengthened concrete cube.

To consider the effect of cement paste in the improvement of compressive strength, the strength-improvement factor is defined in Equation (1).

$$SIF = \frac{RSR_{st}}{RSR_{ns}} \quad (1)$$

where SIF = Strength-improvement factor

$RSR_{st}$  = Remaining strength ratio of strengthened concrete cube after recompression

$RSR_{ns}$  = Remaining strength ratio of non-strengthened concrete cube after recompression

If SIF is greater than 1, it implies that cement paste has an effect on the increase of the ultimate compressive strength after strengthening.

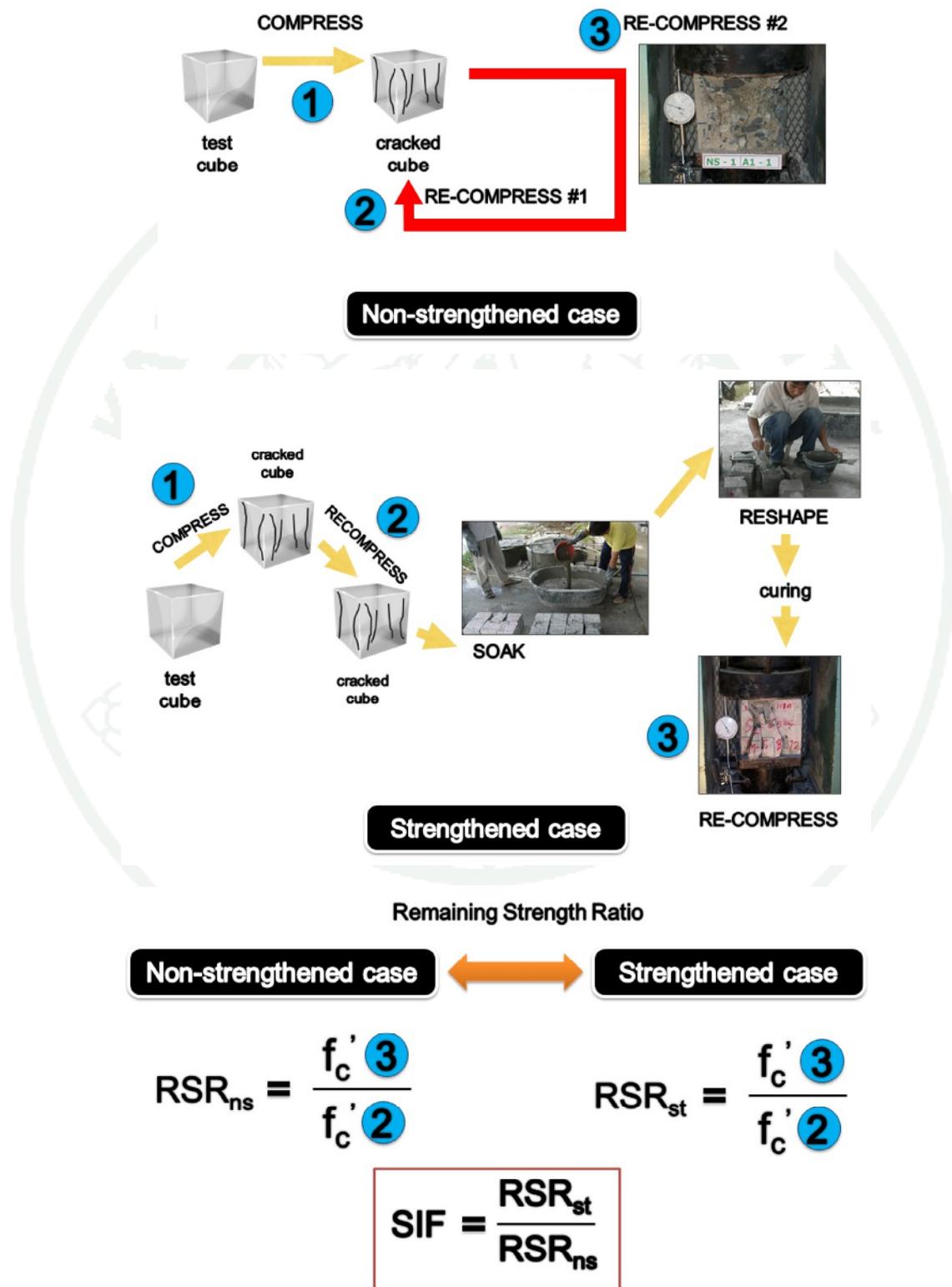


Figure 25 Scheme of overall experiment.

The calculation of strength-improvement factor is shown as follows:

From Appendix Table A1,

$$\begin{aligned} & \text{The average of remaining strength ratio after first recompression} \\ & = (0.928+0.913+0.967+0.873+0.810+0.832)/6 = 0.8871 \end{aligned}$$

$$\begin{aligned} & \text{The average of remaining strength ratio after second recompression} \\ & = (0.833+0.832+0.877+0.764+0.648+0.650)/6 = 0.7673 \end{aligned}$$

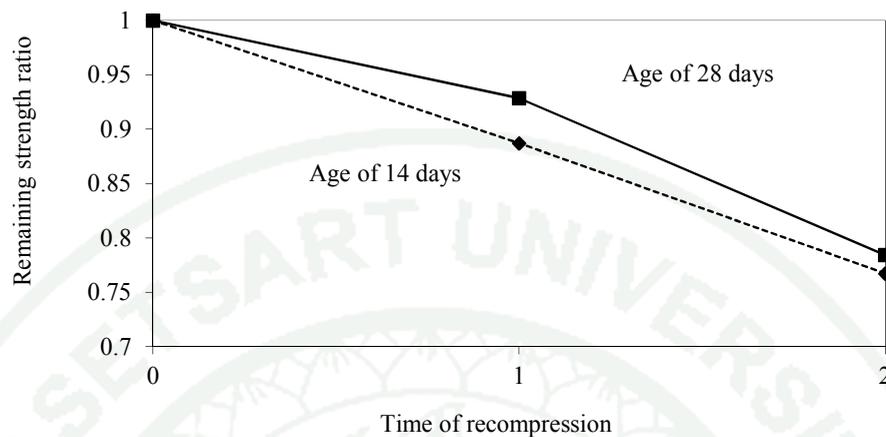
$$\text{Thus, } RSR_{ns} = 0.7673/0.8871 = 0.8649$$

And from Appendix Table A7 (use M1 as example),

$$\begin{aligned} & \text{The average of remaining strength ratio after strengthening (not including the} \\ & \text{maximum and minimum value of ratio), } RSR_{st} \\ & = (0.86+0.74+0.93+0.90+0.82+0.94+0.92+0.83+0.98+0.90)/12 = 0.8813 \end{aligned}$$

$$\text{Therefore, } SIF = RSR_{st} / RSR_{ns} = 0.8813/0.8649 = 1.019 > 1$$

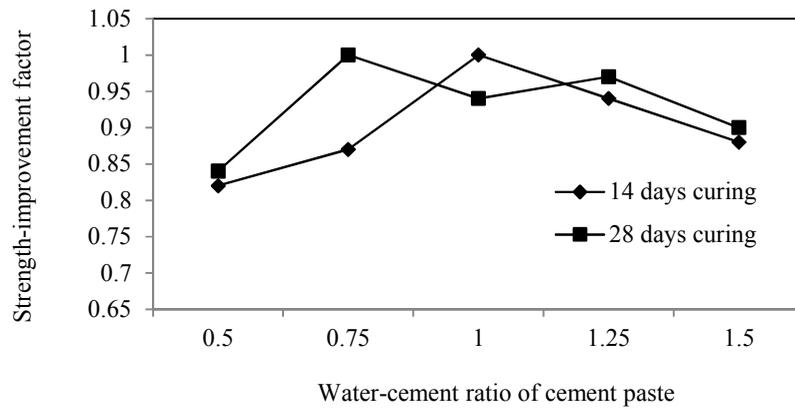
Remaining strength ratio is the proportion of ultimate compressive strength after recompression to the first or previous compression. Figure 26 shows the compressive strength of non-strengthened cubes after recompressed decrease from 100% to 88.71% at the age of 14 days and 100% to 92.85% at the age of 28 days after the first recompression (refer to Appendix Table A1 and Appendix Table A2). Furthermore, in the second recompression, the remaining strength of concrete test cube decreases in higher rate than the first recompression.



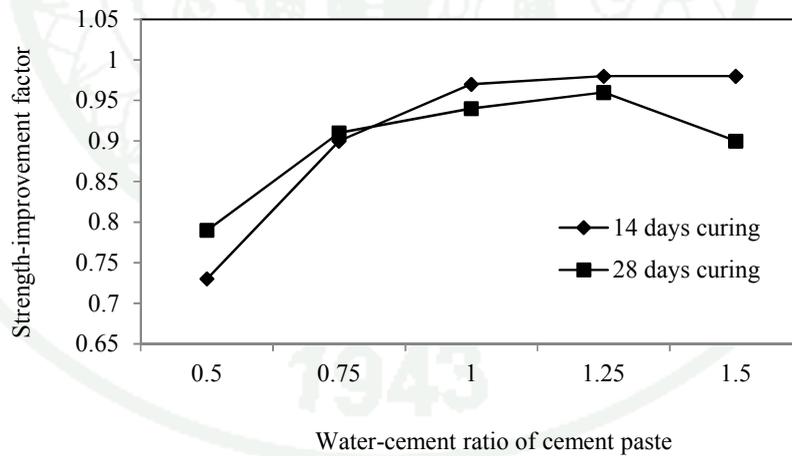
**Figure 26** Remaining strength of concrete test cube in relation to recompression (Non-strengthened case).

On the other hand, the results of the experiment showed that the remaining compressive strength of cracked concrete cube soaked in cement paste is more than the case of the non-strengthened cracked concrete cube as shown in Figure 29 and Figure 30.

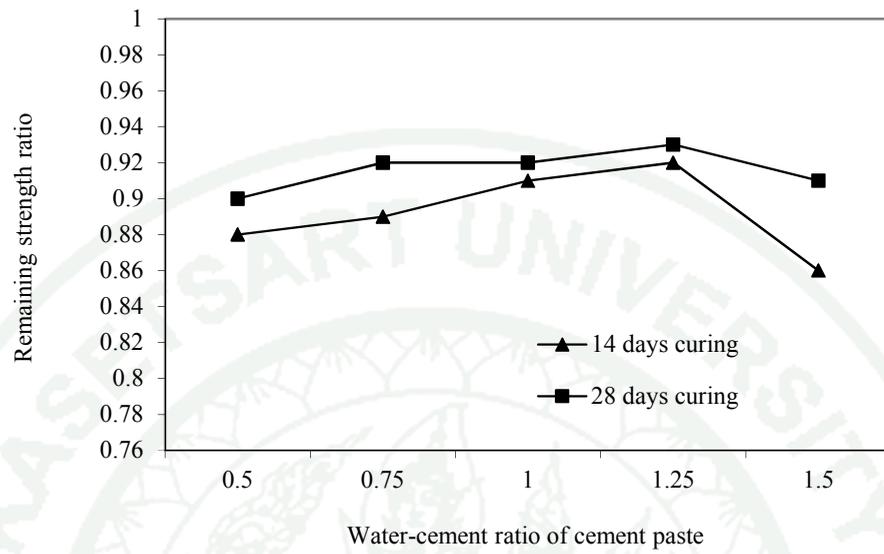
Due to strengthened concrete test cube reshaped by mixed cement paste giving SIF less than 1, as shown in Figure 21 and Figure 22, only the results of strengthened concrete test cube reshaped by Portland cement type I paste are discussed in this paper.



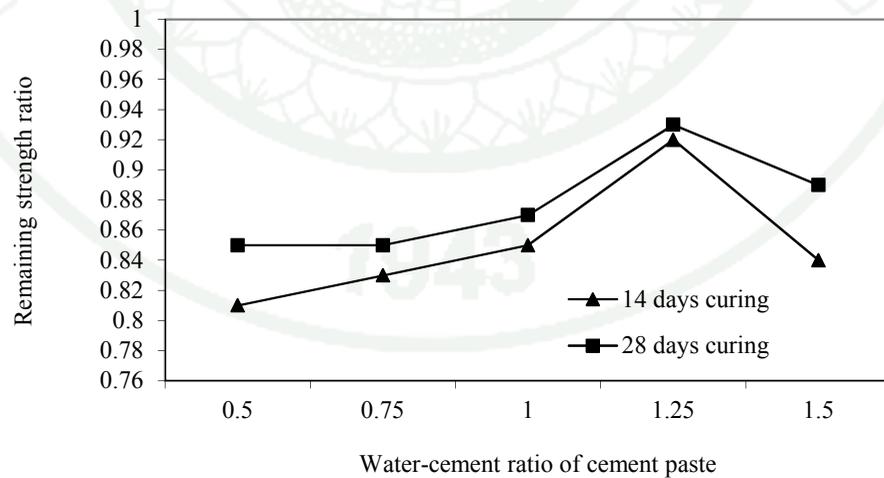
**Figure 27** The relationship between SIF and w/c of cement paste in strengthening of 14 days of age cracked cube reshaped by mixed cement paste by varying the curing times.



**Figure 28** The relationship between SIF and w/c of cement paste in strengthening of 28 days of age cracked cube reshaped by mixed cement paste by varying the curing times.



**Figure 29** The relationship between remaining strength ratio and water-cement ratio of cement paste in strengthening of 14 days of age cracked concrete test cube by varying the curing times in the strengthening.

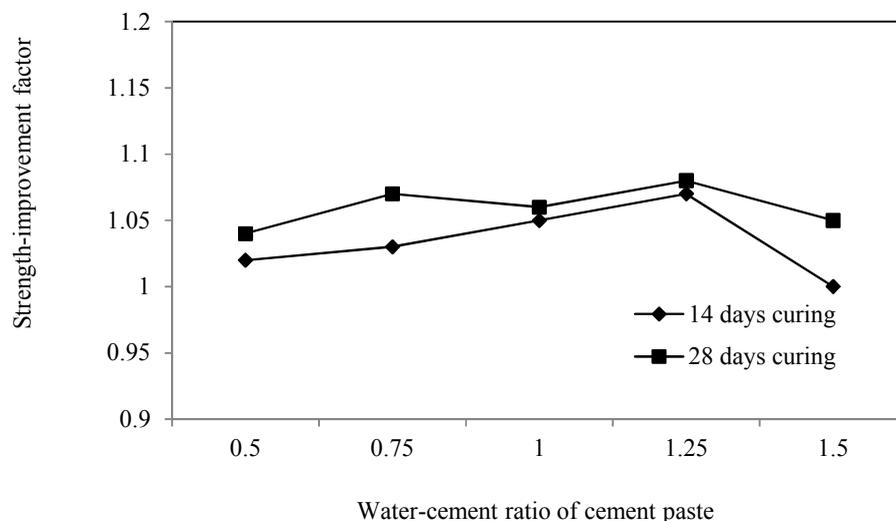


**Figure 30** The relationship between remaining strength ratio and water-cement ratio of cement paste in strengthening of 28 days of age cracked concrete test cube by varying the curing times in the strengthening.

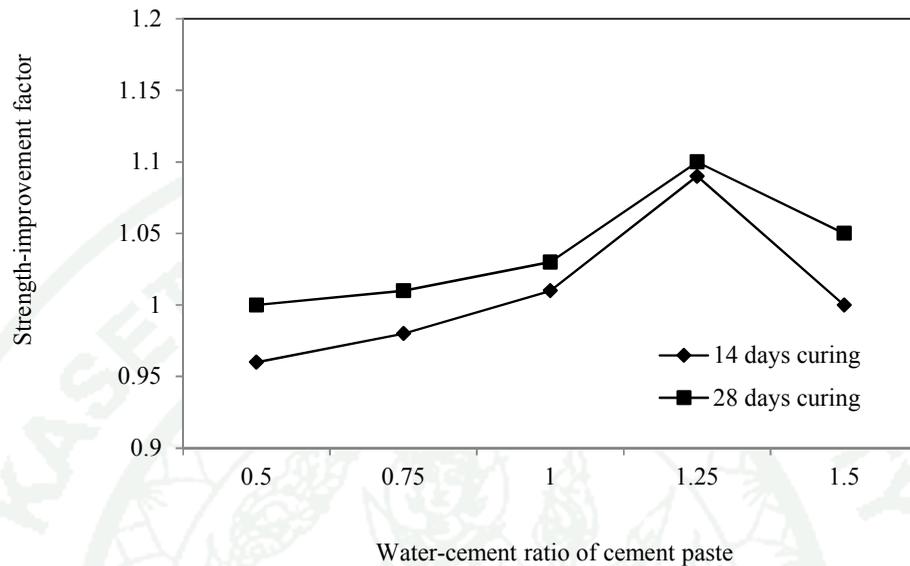
The result indicates that the case of using water-cement ratio of cement paste equal to 1.25 and 28 days of curing time in the strengthening of 28 days of age cracked concrete test cube gives the highest SIF (equal to 1.10) as shown in Figure 32.

Figure 31 shows the result of the strengthening of 14 days of age cracked concrete test cube which gives the same optimum water-cement ratio of cement paste as the case of 28 days of age cube. The maximum SIF of this case is equal to 1.08.

Additionally, the result of strengthening of 28 days of age cracked concrete cube gives higher SIF than strengthening of 14 days of age cracked concrete cube; however, the optimum water-cement ratio is similar.



**Figure 31** The relationship between SIF and w/c of cement paste in strengthening of 14 days of age cracked cube reshaped by Portland cement type I paste by varying the curing times.



**Figure 32** The relationship between SIF and w/c of cement paste in strengthening of 28 days of age cracked cube reshaped by Portland cement type I by varying the curing times.

From both Figure 31 and Figure 32, it can be seen that the SIF has rising value in accordance with water-cement ratio that increases until water-cement ratio equal to 1.25. The main reason of this tendency is consistency of cement paste. Higher viscosity results in lower percolation of cement paste through cracks. But if cement paste has more water in mixing as case of water-cement ratio equal to 1.5, it has excessive liquidity which causes SIF to become lower value. Therefore, 1.25 of water-cement ratio of cement paste is the most appropriate mix for strengthening.

Figure 32 shows that strength-improvement factor of cracked cube strengthened by 0.5 and 0.75 water-cement ratio in mixture of cement paste and 28 days curing is less than 1 due to the compression testing machine.

Additionally, from the observation it was found that almost all concrete cubes in this research have similar failure mode, which is normal failure called shear-bond cracks as shown in Figure 33.



**Figure 33** Failure patterns of test cubes in strengthened case.

## 2. Application and Case Study

The result of construction reveals that the concrete cube is able to be used as masonry unit in unreinforced masonry wall for one-story house by using normal work equipment and skill in brick/blockwork.

Due to the fact that a concrete cube is acquired from actual concrete construction project, not the masonry unit manufactory in particularly, there are different aspects of practice that have to be considered. Table 4 shows the quantity of material used in the construction and total cost.



**Figure 34** One-story house built from concrete cubes.

**Table 4** Bill of quantity and actual cost of construction.

Item	Description	Unit of material	Material		Total (Baht)
			Unit cost (Baht)	Quantity	
<b>Roofing</b>					
1	Angle ridge	sheet	45	15	675
2	Tile roofing	sheet	57	150	8,550
3	Tile clip	pcs	3	180	540
<b>Roof structure</b>					
4	Purlin C-2"x4"x6 m	work	24,000	1	24,000
5	Rafter C-2"x5"x6 m		(labor		
6	Ridge C-2"x6"x6 m		5,000)		
7	Major tie beam C-2"x6"x6 m				
8	Minor tie beam C-2"x4"x6 m				
9	King post C-2"x5"x1 m				
10	Tie C-2"x4"x1 m				
11	Tie C-2"x4"x1.5 m				
12	Primer and Paint				
<b>Ceiling</b>					
13	Ceiling frame	ft <sup>2</sup>	1,200	7.18	8,616
14	Cement board 0.04x1.2x2.4 m	pcs	6	175	1,050
<b>Bond beam</b>					
15	Portland cement type I	bag	135	3	405
16	Sand	m <sup>3</sup>	400	0.5	200
17	Coarse aggregate	m <sup>3</sup>	500	0.5	250
18	Reinforcement steel (RB 9)	m	10	80	800
19	Steel stirrups (RB 6)	m	6	70	420
20	Formwork 1"x8"x4 m	pcs	220	10	2,200

**Table 4** (Continued).

Item	Description	Unit of material	Material		Total (Baht)
			Unit cost (Baht)	Quantity	
<b>Doors and windows</b>					
21	Windowframes	pcs	0	5	0
22	Doorframes	sum	5,865	1	5,865
23	Jalousie	set	120	7	840
24	Glass	pcs	17	84	1,428
25	Insect screen	sum	2,000	1	2,000
26	Window steel (DB 12)	sum	2,250	1	2,250
27	Door 0.90x2 m	pcs	700	1	700
28	Door 0.70x2 m	pcs	500	1	500
29	Door hardware	sum	250	1	250
30	Paint	pcs	100	2	200
31	Varnish	bottle	20	2	40
<b>Wall paint</b>					
32	Primer	pcs	600	2	1,200
33	Paint	pcs	2,600	1	2,600
<b>Floor</b>					
34	Floor tiles 12"x12"	m <sup>2</sup>	154	24	3,696
35	Portland cement type I	bag	135	17	2,295
36	Mixed cement	bag	115	7	805
37	Sand	m <sup>3</sup>	400	2.5	1,000
38	Coarse Aggregate	m <sup>3</sup>	500	2.5	1,250
39	Reinforcement steel (RB 6)	m	5	160	800

**Table 4** (Continued).

Item	Description	Unit of material	Material		Total (Baht)
			Unit cost (Baht)	Quantity	
<b>Foundation</b>					
40	Ready mixed concrete	m <sup>3</sup>	2,235	7.5	16,763
41	Lean concrete	m <sup>3</sup>	2,060	1.2	2,472
42	Sand	m <sup>3</sup>	400	11.2	4,480
43	Reinforcement steel (DB 12)	m	130	46	5,980
44	Iron wires	kg	60	3	180
<b>Masonry</b>					
45	Concrete cube	pcs	0	1,980	0
46	Mixed cement	bag	115	19	2,185
47	Sand	m <sup>3</sup>	400	1.2	480
<b>Total</b>					<b>107,965</b>

Firstly, since the work face of concrete cube is 15x15 cm, a large amount of mortar requires filling in of joints. Otherwise, the mortar has to be compacted by rod or trowel. All blocks are laid on a full bed of mortar with all cross joints and bed joints filled as shown in Figure 35 and Figure 36.

Secondly, in order to increase the bonding between each concrete cube, the side-face of concrete cube is roughened by concrete nail as shown in Figure 37.

Additionally, curing is an important factor which affects not only the bonding of masonry units but also the strength of masonry wall as shown in Figure 38.



**Figure 35** Method of laying cube on mortar bed.

Thirdly, as the size of concrete cube is not exactly 15 cm, it is important to dry bond the course to avoid unequal joint. But joint thickness has to be adjusted in the 1 to 2 cm range.

Fourthly, From Figure 39, due to the fact that the door and window frames that have size 15 cm are scarce and expensive, the smaller size of frame is more appropriate. Meanwhile if a door or window frame is smaller than thickness of wall, a concrete cube should not be laid above the door or window. But if the frame size is equal to the thickness of wall, the calculation is a must.



**Figure 36** Method of filling mortar in cross joint.



**Figure 37** The concrete cube roughened by concrete nail.



**Figure 38** Curing of concrete cube masonry structure.



**Figure 39** Installation of window and door frames.



**Figure 39** (Continued).



**Figure 39** (Continued).

Fifthly, since there are no lintels in this structure, bond beam is used to join the entire masonry structure together and distribute the load from the roof along the length of wall as shown in Figure 40.



**Figure 40** Formwork of cast in-situ bond beam.

Sixthly, in order to fasten the roof frame to the masonry wall, a steel rod is embedded in the concrete block and bond beam during the casting as shown in Figure 41.



**Figure 41** Detail for holding down of roof on concrete cube masonry structure.

Lastly, the properties of soil and structural detail of footing are especially important in the design and calculation since a weight of concrete cube masonry structure is more than other conventional masonry structures.

### **3. A Comparison with Other Masonry Units**

The result of this part is demonstrated as Table 5.

**Table 5** The comparison of masonry unit properties.

Properties	Clay brick <sup>1</sup>	Concrete block <sup>1</sup>	Autoclaved aerated concrete block <sup>1</sup>	Concrete cube
Size (cm)	7x15x6	20x40x7	20x60x7.5 20x60x10	15x15x15
Weight (kg/m <sup>2</sup> )	130	115	50	360
No. of units (units/m <sup>2</sup> )	120	12.5	8.33	44.44
Compressive strength (kg/cm <sup>2</sup> )	20-40	10-15	35-80	180-440 (varying)*
Thickness of mortar joint (cm)	1.5-2.0	1.0-1.5	0.23	1.0-2.0
Installation (m <sup>2</sup> /day)	6-8	12	15-25	8-10
Mortar Type	Mixed cement	Mixed cement	Lightweight block masonry mortar	Mixed cement

\* Strength of concrete cube depends on a part of structure, which concrete cube is molded for testing.

**Source:** Chatchavan (2008)

Although a weight of concrete cube is more than other masonry units, it is not the important issue because utilization of concrete cube is the reduction of amount of construction waste that is produced when construction is finished. This is a significant advantage of reusing of concrete cube.

This study reuse residual concrete cube from highway construction as masonry unit; therefore, there is no price, as shown in Table 6.

**Table 6** The comparison of masonry unit price.

Topic	Clay brick (7x16x3.5 cm)	Concrete Block (19x39x7 cm)	Autoclaved aerated concrete block (20x60x7.5 cm)	Concrete cube (15x15x15 cm)
Unit price (Baht)	0.83 <sup>1</sup>	4.50 <sup>1</sup>	18-23*	0
Material cost (Baht/m <sup>2</sup> )	100*	56*	150-195 <sup>1</sup>	0

\* Approximate values from calculation

**Source:** Bureau of Trade and Economic indices (2010)

The fact that the reusing of concrete cube is not deed for marketing, the utilization depends on demand of locals, owner of project or anybody that is involved in the construction. For this reason, the transportation cost of concrete cube is not able to be compared with other masonry unit where the transportation cost is specified by the retailer. However, in the case of using as masonry in similar quantities of work, the number of transits of concrete cubes is more than others because of weight. Additionally, the labor cost in work of concrete cube masonry is not distinctive from others.

## CONCLUSION AND RECOMMENDATION

### Conclusion

1. The cement paste can be used in the strengthening of cracked concrete test cube.
2. The most appropriate method for the strengthening of cracked concrete test cube at both 14 and 28 days of age is the soaking in Portland cement type I paste (1.25:1 of water-cement ratio) for 30 minutes and continuously stirred simultaneously, reshaped by using Portland cement type I paste and cured in water for 28 days which has the highest enhancement of the ultimate compressive strength and has enough strength to use as masonry unit in load bearing wall.
3. The strengthened cracked concrete test cube can be used as a masonry unit in masonry structure, although there are circumstances to be concerned about with this practice.
4. The one-story house constructed by concrete test cubes is better than that constructed by conventional masonry units in terms of economy and strength capacity. Furthermore, the significant advantage of using concrete cube as masonry unit in structure is the reduction of amount of construction waste especially in the highway construction project in Thailand.

### **Recommendation**

1. Due to the fact that cracked concrete cube has better compressive strength than other masonry unit, the remaining strength of cracked concrete cube is adequate for use as masonry unit in conventional structure such as one-story house, as in case study in this research, without soaking in cement paste.

2. For the purpose of using as masonry unit in load bearing structure, cracked concrete test cube should be reshaped by Portland cement type I paste. But for the important structure or heavy load resistance structure, the strengthening by soaking in cement paste, as in this research, is necessary.

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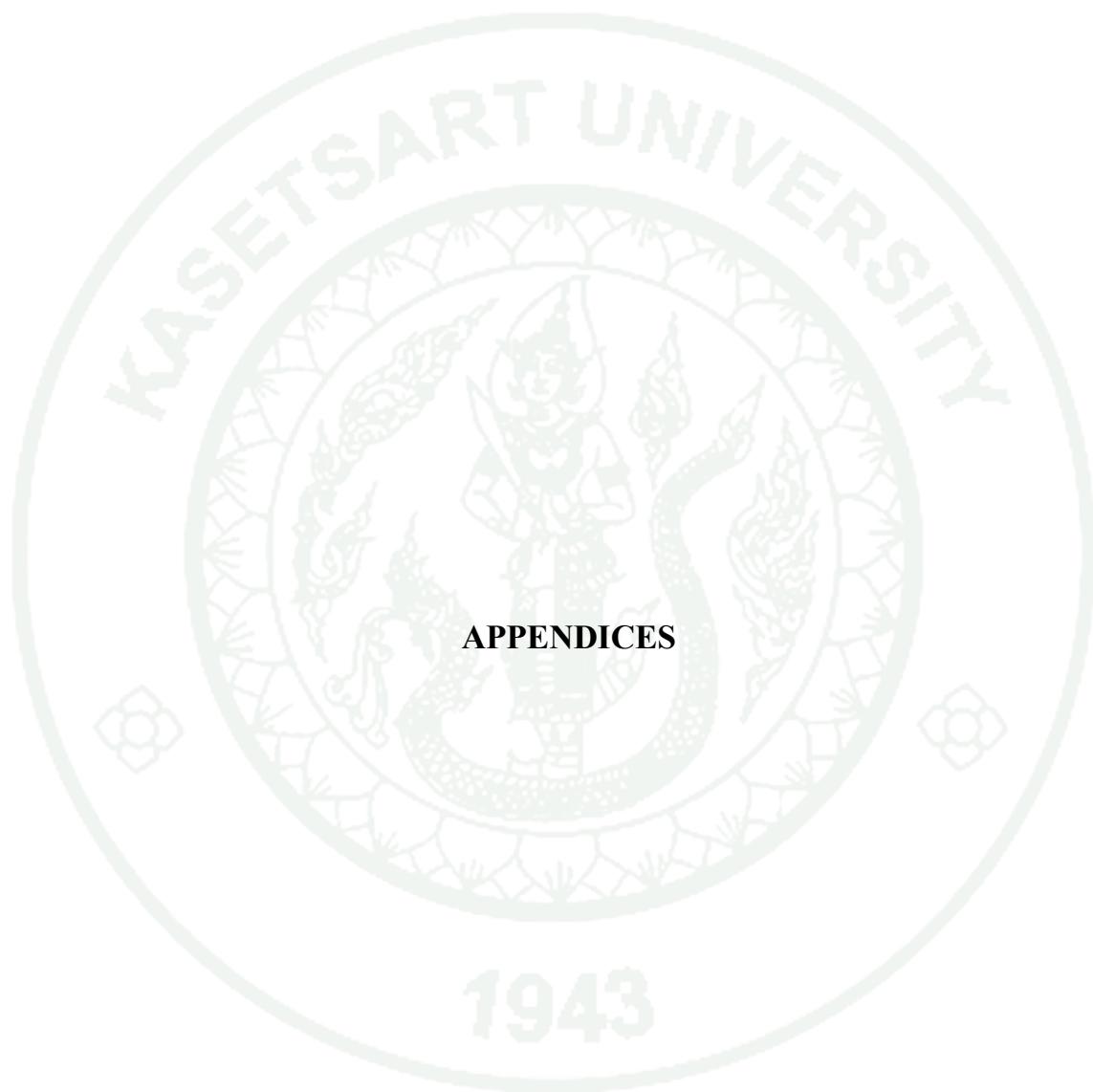
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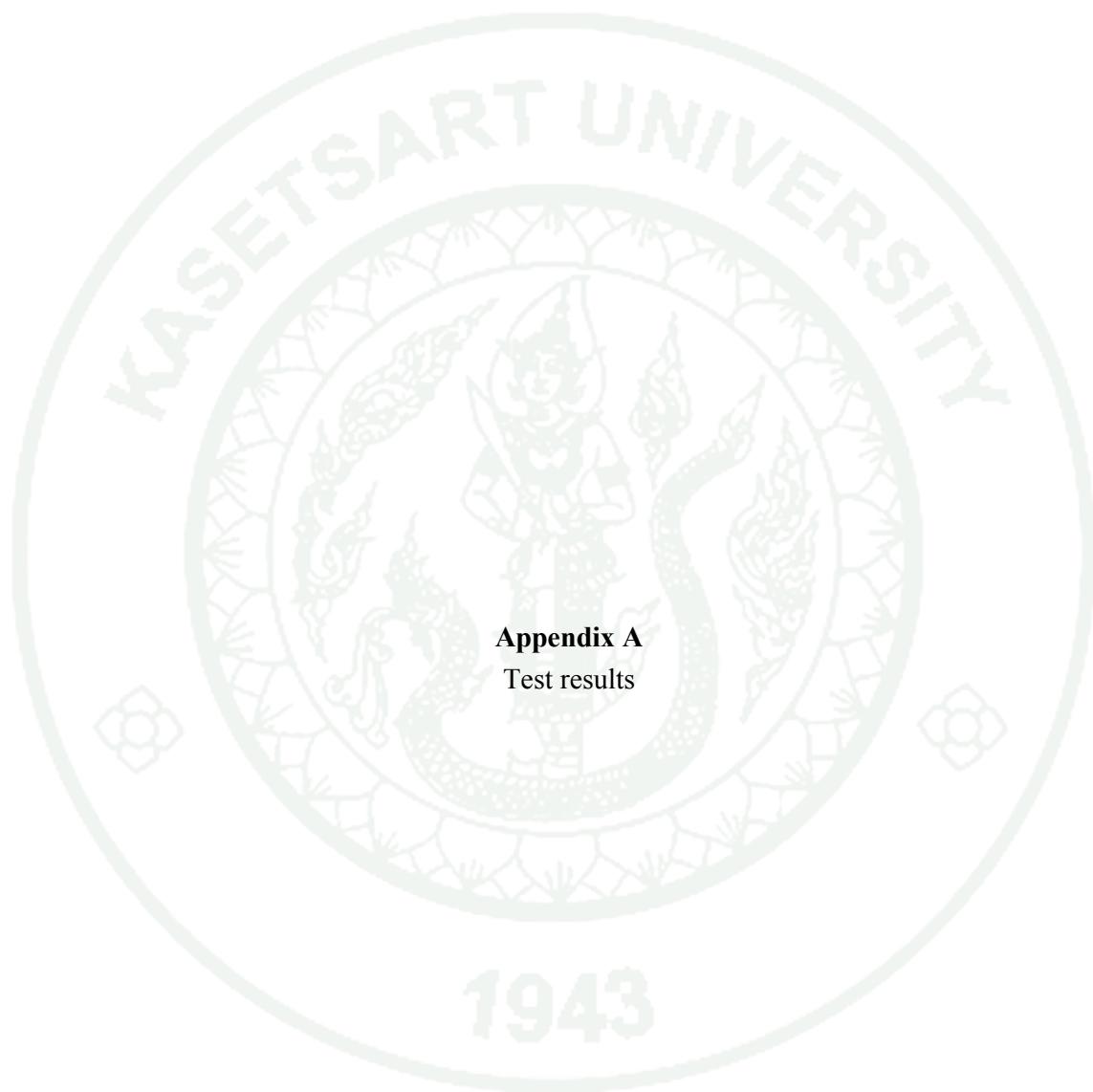
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**APPENDICES**



**Appendix A**  
Test results

**Appendix Table A1** Result of compressive strength testing of concrete test cubes

14 days of age (Non-strengthened case).

Specimens	Compressive Strength (ksc)			Remaining strength after recompression	
	First compression	Recompression		1	2
		1	2		
NS 1-A1-1	330.73	289.95	240.12	0.877	0.726
NS 1-A1-2	326.20	317.14	299.04	0.972	0.917
NS 1-A1-3	348.85	326.20	299.01	0.935	0.857
Average	335.26	311.10	279.38	0.928	0.833
NS 1-A2-1	357.91	348.85	330.73	0.975	0.924
NS 1-A2-2	262.77	231.06	203.87	0.879	0.776
NS 1-A2-3	353.38	312.61	280.89	0.885	0.795
Average	324.69	297.50	271.83	0.913	0.832
NS 2-A3-1	289.95	280.89	253.71	0.969	0.875
NS 2-A3-2	330.73	308.08	276.36	0.932	0.836
NS 2-A3-3	285.42	285.42	262.77	1.000	0.921
Average	302.03	291.46	264.28	0.967	0.877
NS 2-A4-1	321.67	276.36	231.06	0.859	0.718
NS 2-A4-2	339.79	303.55	280.89	0.893	0.827
NS 2-A4-3	303.55	262.77	226.53	0.866	0.746
Average	321.67	280.89	246.16	0.873	0.764
NS 3-A5-1	335.26	271.83	226.53	0.811	0.676
NS 3-A5-2	285.42	258.24	217.47	0.905	0.762
NS 3-A5-3	430.40	308.08	217.47	0.716	0.505
Average	350.36	279.38	220.49	0.810	0.648
NS 3-A6-1	330.73	271.83	212.93	0.822	0.644
NS 3-A6-2	312.61	262.77	212.93	0.841	0.681
NS 3-A6-3	326.20	271.83	203.87	0.833	0.625
Average	323.18	268.81	209.91	0.832	0.650

**Appendix Table A2** Result of compressive strength testing of concrete test cubes  
28 days of age (Non-strengthened case).

Specimens	Compressive stress (ksc)			Remaining strength after recompression	
	First compression	Recompression		1	2
		1	2		
NS 1-B1-1	502.89	457.58	357.91	0.910	0.712
NS 1-B1-2	480.24	425.87	344.32	0.887	0.717
NS 1-B1-3	443.99	425.87	380.56	0.959	0.857
Average	475.71	436.44	360.93	0.919	0.762
NS 1-B2-1	471.17	448.52	416.81	0.952	0.885
NS 1-B2-2	439.46	425.87	394.16	0.969	0.897
NS 1-B2-3	448.52	412.28	339.79	0.919	0.758
Average	453.05	428.89	383.58	0.947	0.846
NS 2-B3-1	471.17	421.34	308.08	0.894	0.654
NS 2-B3-2	421.34	416.81	389.63	0.989	0.925
NS 2-B3-3	493.83	421.34	380.56	0.853	0.771
Average	462.11	419.83	359.42	0.912	0.783
NS 2-B4-1	502.89	448.52	394.16	0.892	0.784
NS 2-B4-2	484.77	462.11	434.93	0.953	0.897
NS 2-B4-3	407.75	353.38	258.24	0.867	0.633
Average	465.13	421.34	362.44	0.904	0.771
NS 3-B5-1	439.46	412.28	371.50	0.938	0.845
NS 3-B5-2	357.91	344.32	271.83	0.962	0.759
NS 3-B5-3	462.11	457.58	353.38	0.990	0.765
Average	419.83	404.73	332.24	0.963	0.790
NS 3-B6-1	416.81	389.63	339.79	0.935	0.815
NS 3-B6-2	462.11	394.16	258.24	0.853	0.559
NS 3-B6-3	434.93	430.40	385.09	0.990	0.885
Average	437.95	404.73	327.71	0.926	0.753

**Appendix Table A3** Result of compressive strength testing of concrete test cubes  
14 days of age reshaped by mixed cement paste and cured at  
14 days (Strengthened case).

Specimens	Compressive stress (ksc)		Remaining strength ratio
	Before strengthening	After strengthening	
MT1-A1	380.56	344.32	0.90
MT1-A2	421.34	353.38	0.84
MT1-A3	380.56	321.67	0.85
MT1-A4	430.40	285.42	0.66
MT1-A5	339.79	158.57	0.47
MT1-A6	394.16	203.87	0.52
	Average		0.71
MT2-A1	416.81	376.03	0.90
MT2-A2	430.40	335.26	0.78
MT2-A3	425.87	271.83	0.64
MT2-A4	389.63	194.81	0.50
MT2-A5	394.16	308.08	0.78
MT2-A6	434.93	389.63	0.90
	Average		0.75
MT3-A1	543.66	498.36	0.92
MT3-A2	489.30	471.17	0.96
MT3-A3	407.75	344.32	0.84
MT3-A4	412.28	317.14	0.77
MT3-A5	366.97	303.55	0.83
MT3-A6	430.40	385.09	0.89
	Average		0.87

**Appendix Table A3** (Continued).

Specimens	Compressive stress (ksc)		Remaining strength ratio
	Before strengthening	After strengthening	
MT4-A1	493.83	489.30	0.99
MT4-A2	471.17	385.09	0.82
MT4-A3	543.66	240.12	0.44
MT4-A4	434.93	380.56	0.87
MT4-A5	502.89	426.81	0.83
MT4-A6	466.64	434.93	0.94
	Average		0.82
MT5-A1	371.50	226.53	0.61
MT5-A2	425.87	339.79	0.80
MT5-A3	448.52	362.44	0.81
MT5-A4	425.87	389.63	0.91
MT5-A5	366.97	312.61	0.85
MT5-A6	389.63	235.59	0.60
	Average		0.76

**Appendix Table A4** Result of compressive strength testing of concrete test cubes

14 days of age reshaped by mixed cement paste and cured at

28 days (Strengthened case).

Specimens	Compressive stress (ksc)		Remaining strength ratio
	Before strengthening	After strengthening	
MT1-A7	403.22	362.44	0.90
MT1-A8	394.16	317.14	0.80
MT1-A9	453.05	335.26	0.74
MT1-A10	412.28	303.55	0.74
MT1-A11	385.09	226.53	0.59
MT1-A12	385.09	226.53	0.59
	Average		0.73
MT2-A7	407.75	380.56	0.93
MT2-A8	421.34	407.75	0.97
MT2-A9	425.87	380.56	0.89
MT2-A10	448.52	394.16	0.88
MT2-A11	421.34	271.83	0.65
MT2-A12	407.75	348.85	0.86
	Average		0.86
MT3-A7	357.91	285.42	0.80
MT3-A8	471.17	484.77	1.03
MT3-A9	498.36	471.17	0.95
MT3-A10	434.93	303.55	0.70
MT3-A11	588.97	389.63	0.66
MT3-A12	416.81	312.61	0.75
	Average		0.81

**Appendix Table A4** (Continued).

Specimens	Compressive stress (ksc)		Remaining strength ratio
	Before strengthening	After strengthening	
MT4-A7	453.05	344.32	0.76
MT4-A8	493.83	453.05	0.92
MT4-A9	457.58	339.79	0.74
MT4-A10	475.71	398.69	0.84
MT4-A11	439.46	371.50	0.85
MT4-A12	534.60	493.83	0.92
	Average		0.84
MT5-A7	457.58	385.09	0.84
MT5-A8	434.93	271.83	0.62
MT5-A9	439.46	348.85	0.79
MT5-A10	412.28	376.03	0.91
MT5-A11	430.40	308.08	0.72
MT5-A12	403.22	312.61	0.78
	Average		0.78

**Appendix Table A5** Result of compressive strength testing of concrete test cubes  
28 days of age reshaped by mixed cement paste and cured at  
14 days (Strengthened case).

Specimens	Compressive stress (ksc)		Remaining strength ratio
	Before strengthening	After strengthening	
MT1-B1	339.79	154.04	0.45
MT1-B2	380.56	289.95	0.76
MT1-B3	457.58	203.87	0.45
MT1-B4	371.50	203.87	0.55
MT1-B5	339.79	212.93	0.63
MT1-B6	335.26	294.48	0.88
	Average		0.62
MT2-B1	443.99	357.91	0.81
MT2-B2	412.28	357.91	0.87
MT2-B3	443.99	158.57	0.36
MT2-B4	398.69	303.55	0.76
MT2-B5	366.67	317.14	0.86
MT2-B6	453.05	412.28	0.91
	Average		0.76
MT3-B1	525.54	339.79	0.65
MT3-B2	308.08	240.12	0.78
MT3-B3	389.63	348.85	0.90
MT3-B4	344.32	303.55	0.88
MT3-B5	430.40	357.91	0.83
MT3-B6	498.36	430.40	0.86
	Average		0.82

**Appendix Table A5** (Continued).

Specimens	Compressive stress (ksc)		Remaining strength ratio
	Before strengthening	After strengthening	
MT4-B1	380.56	303.55	0.80
MT4-B2	407.75	326.20	0.80
MT4-B3	525.54	462.11	0.88
MT4-B4	498.36	421.34	0.85
MT4-B5	330.73	299.01	0.90
MT4-B6	317.14	240.12	0.76
	Average		0.83
MT5-B1	376.03	285.42	0.76
MT5-B2	385.09	335.26	0.87
MT5-B3	362.44	294.48	0.81
MT5-B4	421.34	385.09	0.91
MT5-B5	457.58	326.20	0.71
MT5-B6	471.17	434.93	0.92
	Average		0.83

**Appendix Table A6** Result of compressive strength testing of concrete test cubes  
28 days of age reshaped by mixed cement paste and cured at  
28 days (Strengthened case).

Specimens	Compressive stress (ksc)		Remaining strength ratio
	Before strengthening	After strengthening	
MT1-B7	353.38	258.24	0.73
MT1-B8	335.26	194.81	0.58
MT1-B9	466.64	276.36	0.59
MT1-B10	380.56	258.24	0.68
MT1-B11	376.03	226.53	0.60
MT1-B12	416.81	339.79	0.82
	Average		0.67
MT2-B7	321.67	172.16	0.54
MT2-B8	335.26	262.77	0.78
MT2-B9	407.75	385.09	0.94
MT2-B10	475.71	380.56	0.80
MT2-B11	425.87	376.03	0.88
MT2-B12	407.75	276.36	0.68
	Average		0.77
MT3-B7	498.36	416.81	0.84
MT3-B8	534.60	430.40	0.81
MT3-B9	453.05	371.50	0.82
MT3-B10	498.36	389.63	0.78
MT3-B11	471.17	326.20	0.69
MT3-B12	394.16	330.73	0.84
	Average		0.80

**Appendix Table A6** (Continued).

Specimens	Compressive stress (ksc)		Remaining strength ratio
	Before strengthening	After strengthening	
MT4-B7	453.05	262.77	0.58
MT4-B8	475.71	462.11	0.97
MT4-B9	484.77	453.05	0.93
MT4-B10	394.16	317.14	0.80
MT4-B11	430.40	348.85	0.81
MT4-B12	353.38	276.36	0.78
	Average		0.81
MT5-B7	443.99	398.69	0.90
MT5-B8	317.14	235.59	0.74
MT5-B9	516.48	489.30	0.95
MT5-B10	416.81	258.24	0.62
MT5-B11	430.40	203.87	0.47
MT5-B12	457.58	398.69	0.87
	Average		0.76

**Appendix Table A7** Result of compressive strength testing of concrete test cubes  
 14 days of age reshaped by Portland cement type I paste  
 and cured at 14 days (Strengthened case).

Specimens	Compressive stress (ksc)		Remaining strength ratio
	Before strengthening	After strengthening	
M1-A1	385.09	330.73	0.86
M1-A2	420.26	310.15	0.74
M1-A3	430.40	398.69	0.93
M1-A4	362.44	326.20	0.90
M1-A5	425.87	348.85	0.82
M1-A6	385.09	280.89	0.73
M1-A7	380.56	357.91	0.94
M1-A8	394.16	362.44	0.92
M1-A9	412.28	498.36	1.21
M1-A10	353.38	294.48	0.83
M1-A11	430.40	421.34	0.98
M1-A12	403.22	362.44	0.90
M2-A1	385.09	439.46	1.14
M2-A2	457.58	321.67	0.70
M2-A3	471.17	399.79	0.85
M2-A4	430.40	366.97	0.85
M2-A5	339.79	367.55	1.08
M2-A6	385.09	353.38	0.92
M2-A7	271.83	222.00	0.82
M2-A8	262.77	208.40	0.79
M2-A9	502.89	453.05	0.90
M2-A10	484.77	430.40	0.89
M2-A11	466.64	407.75	0.87
M2-A12	484.77	430.40	0.89

**Appendix Table A7** (Continued).

Specimens	Compressive stress (ksc)		Remaining strength ratio
	Before strengthening	After strengthening	
M3-A1	430.40	376.03	0.87
M3-A2	420.57	446.79	1.06
M3-A3	430.40	376.03	0.87
M3-A4	443.99	353.38	0.80
M3-A5	397.22	308.55	0.78
M3-A6	421.34	344.32	0.82
M3-A7	425.87	434.93	1.02
M3-A8	439.46	466.64	1.06
M3-A9	398.69	421.34	1.06
M3-A10	475.71	430.40	0.90
M3-A11	443.99	416.81	0.94
M3-A12	453.05	416.81	0.92
M4-A1	434.93	421.34	0.97
M4-A2	434.93	376.03	0.86
M4-A3	434.93	405.87	0.93
M4-A4	430.40	394.16	0.92
M4-A5	362.44	321.67	0.89
M4-A6	403.22	331.20	0.82
M4-A7	400.16	356.03	0.89
M4-A8	412.28	406.81	0.99
M4-A9	440.40	399.81	0.91
M4-A10	394.16	407.75	1.03
M4-A11	453.05	425.87	0.94
M4-A12	453.05	430.40	0.95

**Appendix Table A7** (Continued).

Specimens	Compressive stress (ksc)		Remaining strength ratio
	Before strengthening	After strengthening	
M5-A1	439.46	366.81	0.83
M5-A2	434.93	394.16	0.91
M5-A3	339.79	231.06	0.68
M5-A4	412.28	371.50	0.90
M5-A5	448.52	394.93	0.88
M5-A6	457.58	457.58	1.00
M5-A7	407.75	369.63	0.91
M5-A8	453.05	421.34	0.93
M5-A9	462.11	378.52	0.82
M5-A10	439.46	258.24	0.59
M5-A11	462.11	420.52	0.91
M5-A12	457.58	399.46	0.87

**Appendix Table A8** Result of compressive strength testing of concrete test cubes

14 days of age reshaped by Portland cement type I paste

and cured at 28 days (Strengthened case).

Specimens	Compressive stress (ksc)		Remaining strength ratio
	Before strengthening	After strengthening	
M1-A13	430.40	335.26	0.78
M1-A14	453.05	407.75	0.90
M1-A15	430.40	357.91	0.83
M1-A16	453.05	294.48	0.65
M1-A17	439.46	289.95	0.66
M1-A18	421.34	403.22	0.96
M1-A19	366.97	362.44	0.99
M1-A20	398.69	394.16	0.99
M1-A21	366.97	353.38	0.96
M1-A22	371.50	412.28	1.11
M1-A23	530.07	507.42	0.96
M1-A24	489.30	484.77	0.99
M2-A13	407.75	371.50	0.91
M2-A14	421.34	380.56	0.90
M2-A15	430.40	421.34	0.98
M2-A16	407.75	367.75	0.90
M2-A17	362.44	351.50	0.97
M2-A18	362.44	294.48	0.81
M2-A19	457.58	430.40	0.94
M2-A20	498.36	404.77	0.81
M2-A21	294.48	285.42	0.97
M2-A22	285.42	289.95	1.02
M2-A23	380.56	353.38	0.93
M2-A24	453.05	416.81	0.92

**Appendix Table A8** (Continued).

Specimens	Compressive stress (ksc)		Remaining strength ratio
	Before strengthening	After strengthening	
M3-A13	453.05	401.50	0.89
M3-A14	434.93	421.34	0.97
M3-A15	407.75	380.56	0.93
M3-A16	407.75	380.56	0.93
M3-A17	385.09	403.22	1.05
M3-A18	403.22	416.81	1.03
M3-A19	394.16	385.09	0.98
M3-A20	498.36	412.28	0.83
M3-A21	434.93	371.50	0.85
M3-A22	434.93	326.20	0.75
M3-A23	439.46	402.44	0.92
M3-A24	453.05	376.03	0.83
M4-A13	443.99	385.09	0.87
M4-A14	421.34	385.09	0.91
M4-A15	448.52	434.93	0.97
M4-A16	443.99	480.40	1.08
M4-A17	443.99	453.05	1.02
M4-A18	498.36	462.11	0.93
M4-A19	362.44	308.08	0.85
M4-A20	421.34	312.61	0.74
M4-A21	321.67	262.77	0.82
M4-A22	430.40	244.65	0.57
M4-A23	439.46	421.34	0.96
M4-A24	443.99	471.17	1.06

**Appendix Table A8** (Continued).

Specimens	Compressive stress (ksc)		Remaining strength ratio
	Before strengthening	After strengthening	
M5-A13	471.17	457.58	0.97
M5-A14	376.03	389.63	1.04
M5-A15	443.99	405.87	0.91
M5-A16	448.52	423.99	0.95
M5-A17	439.46	412.28	0.94
M5-A18	434.93	388.40	0.89
M5-A19	380.56	303.55	0.80
M5-A20	457.58	403.05	0.88
M5-A21	471.17	385.09	0.82
M5-A22	484.77	484.77	1.00
M5-A23	498.36	471.17	0.95
M5-A24	389.63	312.22	0.80

**Appendix Table A9** Result of compressive strength testing of concrete test cubes

28 days of age reshaped by Portland cement type I paste

and cured at 14 days (Strengthened case).

Specimens	Compressive stress (ksc)		Remaining strength ratio
	Before strengthening	After strengthening	
M1-B1	443.99	335.26	0.76
M1-B2	380.56	285.42	0.75
M1-B3	376.03	294.48	0.78
M1-B4	407.75	271.83	0.67
M1-B5	430.40	321.67	0.75
M1-B6	425.87	235.59	0.55
M1-B7	407.75	371.50	0.91
M1-B8	362.44	328.85	0.91
M1-B9	385.09	262.77	0.68
M1-B10	385.09	412.28	1.07
M1-B11	412.28	416.81	1.01
M1-B12	425.87	394.16	0.93
M2-B1	453.05	376.03	0.83
M2-B2	353.38	308.08	0.87
M2-B3	339.79	240.12	0.71
M2-B4	339.79	277.14	0.82
M2-B5	448.52	312.61	0.70
M2-B6	453.05	380.56	0.84
M2-B7	480.24	400.40	0.83
M2-B8	443.99	398.69	0.90
M2-B9	489.30	416.81	0.85
M2-B10	475.71	401.34	0.84
M2-B11	507.42	407.75	0.80
M2-B12	475.71	466.64	0.98

**Appendix Table A9** (Continued).

Specimens	Compressive stress (ksc)		Remaining strength ratio
	Before strengthening	After strengthening	
M3-B1	398.99	300.65	0.75
M3-B2	400.40	302.55	0.76
M3-B3	403.22	394.16	0.98
M3-B4	353.05	248.55	0.70
M3-B5	430.40	412.28	0.96
M3-B6	407.75	376.03	0.92
M3-B7	407.75	333.40	0.82
M3-B8	394.16	385.09	0.98
M3-B9	389.63	330.40	0.85
M3-B10	385.09	266.20	0.69
M3-B11	453.05	357.57	0.79
M3-B12	407.75	453.05	1.11
M4-B1	407.75	448.52	1.10
M4-B2	398.69	376.03	0.94
M4-B3	407.75	353.38	0.87
M4-B4	425.87	371.50	0.87
M4-B5	403.22	330.56	0.82
M4-B6	407.75	353.22	0.87
M4-B7	407.75	366.97	0.90
M4-B8	421.34	376.03	0.89
M4-B9	394.16	407.75	1.03
M4-B10	412.28	421.34	1.02
M4-B11	475.71	466.64	0.98
M4-B12	457.58	439.46	0.96

**Appendix Table A9** (Continued).

Specimens	Compressive stress (ksc)		Remaining strength ratio
	Before strengthening	After strengthening	
M5-B1	400.34	330.40	0.83
M5-B2	416.81	339.79	0.82
M5-B3	380.56	371.50	0.98
M5-B4	403.22	338.40	0.84
M5-B5	413.99	298.69	0.72
M5-B6	400.99	295.39	0.74
M5-B7	403.22	363.22	0.90
M5-B8	425.87	471.17	1.11
M5-B9	362.44	285.42	0.79
M5-B10	434.93	394.16	0.91
M5-B11	407.75	348.85	0.86
M5-B12	407.75	271.83	0.67

**Appendix Table A10** Result of compressive strength testing of concrete test cubes  
28 days of age reshaped by Portland cement type I paste  
and cured at 28 days (Strengthened case).

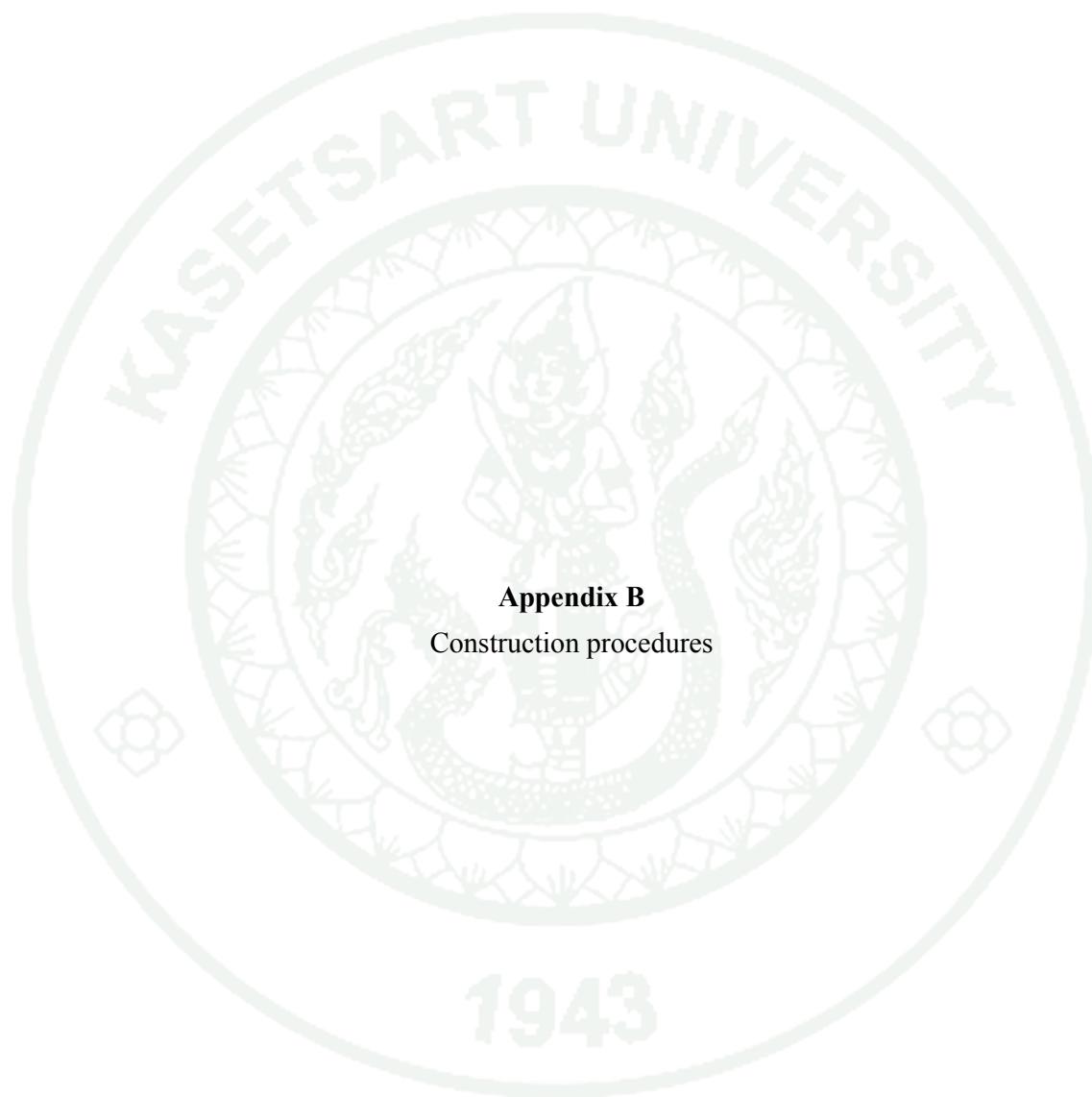
Specimens	Compressive stress (ksc)		Remaining strength ratio
	Before strengthening	After strengthening	
M1-B13	362.44	303.55	0.84
M1-B14	321.67	267.30	0.83
M1-B15	439.46	308.08	0.70
M1-B16	416.81	353.38	0.85
M1-B17	421.34	253.71	0.60
M1-B18	425.87	330.73	0.78
M1-B19	394.16	355.09	0.90
M1-B20	271.83	267.30	0.98
M1-B21	366.67	317.14	0.86
M1-B22	348.85	285.42	0.82
M1-B23	466.64	430.40	0.92
M1-B24	416.81	434.93	1.04
M2-B13	339.79	271.83	0.80
M2-B14	362.44	289.95	0.80
M2-B15	362.44	303.55	0.84
M2-B16	357.91	308.08	0.86
M2-B17	412.28	317.14	0.77
M2-B18	407.75	353.38	0.87
M2-B19	407.75	376.03	0.92
M2-B20	434.93	394.16	0.91
M2-B21	389.63	277.91	0.71
M2-B22	394.16	385.09	0.98
M2-B23	416.81	344.32	0.83
M2-B24	394.16	339.79	0.86

**Appendix Table A10** (Continued).

Specimens	Compressive stress (ksc)		Remaining strength ratio
	Before strengthening	After strengthening	
M3-B13	475.71	439.46	0.92
M3-B14	398.69	380.56	0.95
M3-B15	425.87	443.99	1.04
M3-B16	521.01	344.32	0.66
M3-B17	471.17	326.20	0.69
M3-B18	407.75	289.95	0.71
M3-B19	344.32	298.03	0.87
M3-B20	362.44	334.16	0.92
M3-B21	344.32	430.40	1.25
M3-B22	348.85	330.73	0.95
M3-B23	385.09	330.73	0.86
M3-B24	407.75	326.20	0.80
M4-B13	403.22	348.85	0.87
M4-B14	462.11	430.56	0.93
M4-B15	416.81	366.97	0.88
M4-B16	425.87	276.36	0.65
M4-B17	425.87	453.38	1.06
M4-B18	475.71	439.46	0.92
M4-B19	434.93	407.75	0.94
M4-B20	439.46	430.40	0.98
M4-B21	443.99	398.69	0.90
M4-B22	453.05	416.81	0.92
M4-B23	462.11	430.40	0.93
M4-B24	457.58	484.77	1.06

**Appendix Table A10** (Continued).

Specimens	Compressive stress (ksc)		Remaining strength ratio
	Before strengthening	After strengthening	
M5-B13	416.81	362.44	0.87
M5-B14	462.11	466.64	1.01
M5-B15	448.52	407.75	0.91
M5-B16	471.17	380.56	0.81
M5-B17	448.52	400.99	0.89
M5-B18	480.24	439.46	0.92
M5-B19	434.93	421.34	0.97
M5-B20	471.17	448.52	0.95
M5-B21	439.46	389.63	0.89
M5-B22	394.16	235.59	0.60
M5-B23	466.64	362.44	0.78
M5-B24	457.58	425.87	0.93



**Appendix B**  
Construction procedures



**Appendix Figure B1** Construction Process (Foundation).



**Appendix Figure B1** (Continued).



**Appendix Figure B1** (Continued).



**Appendix Figure B1** (Continued).



**Appendix Figure B1** (Continued).



**Appendix Figure B1** (Continued).



**Appendix Figure B1 (Continued).**



**Appendix Figure B1** (Continued).



**Appendix Figure B2** Preparation of concrete cubes used in the construction.



**Appendix Figure B3** Construction Process (Masonry wall).



**Appendix Figure B3** (Continued).



**Appendix Figure B3** (Continued).



**Appendix Figure B3** (Continued).



**Appendix Figure B3** (Continued).



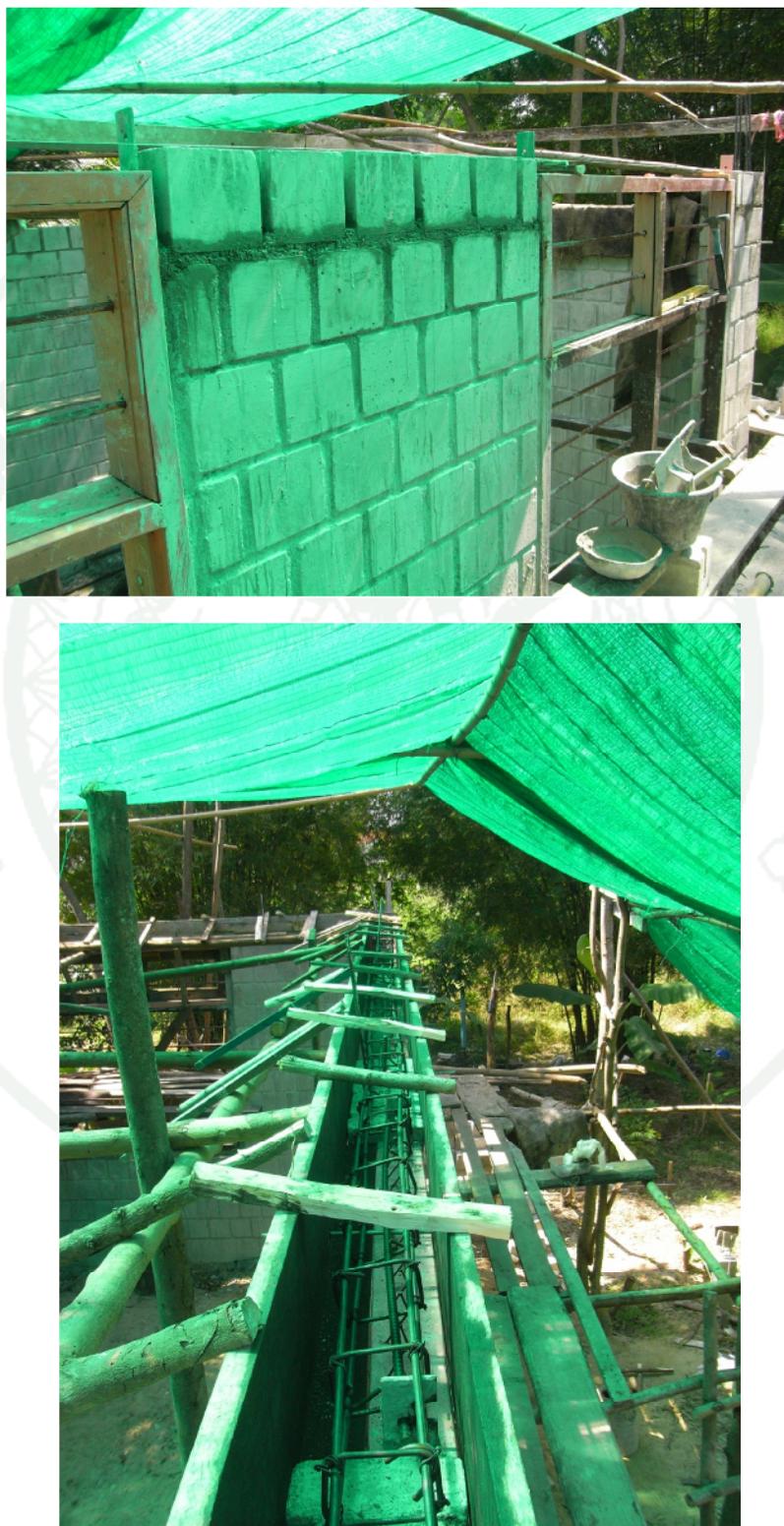
**Appendix Figure B3** (Continued).



**Appendix Figure B3** (Continued).



**Appendix Figure B3** (Continued).



**Appendix Figure B4** Construction Process (Top of wall and roof structure).



**Appendix Figure B4** (Continued).



**Appendix Figure B4** (Continued).

## CIRRICULUM VITAE

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