การจำลองไฟไนต์เอลิเมนต์ของรอยแตกร้าวจากการหดตัวในแผ่นพื้นวางบนดินเนื่องจากการยึดรั้ง

นางสาวเท็ต ธันดาร์ ซอว์

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ลิขสิทธิ์ของจุฬาลงกรณ์มหาวิทยาลัย

FINITE ELEMENT SIMULATIONS OF SHRINKAGE CRACKS IN SLAB-ON-GRADE DUE TO RESTRAINTS

Miss Htet Thandar Soe

จุฬาลงกรณ์มหาวิทยาลัย
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A Thesis Submitted in Partial Fulfillment of the Requirements
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เนื่องจากข้อดีหลายอย่างของแผ่นพื้นวางบนดิน โดยเฉพาะทางด้านราคาและความทนทาน แผ่นพื้นดังกล่าวถูกใช้ในโรงงาน อู่รถยนต์ ทางเท้าสำหรับพื้นที่แข็งแรง และในอาคารที่อยู่อาศัยด้วย อย่างไรก็ตามเรื่องที่สำคัญคือการก่อตัวของรอยแตกร้าวจากการยึดรั้งการเสียรูปของแผ่นพื้น โดยการยึดรั้งที่เป็นไปได้ที่ไม่ยอมให้คอนกรีตเปลี่ยนแปลงปริมาตรได้อย่างอิสระ ได้แก่ แรงเสียดทานระหว่างแผ่นพื้นและชั้นรองพื้น ผลกระทบของเสาเข็มและเสา และลำดับการหล่อคอนกรีต

งานวิจัยนี้มีจุดประสงค์เพื่อเก็บข้อมูลและสังเกตการก่อตัวของรอยแตกร้าวในแผ่นพื้นวางบนดินของสองโรงงาน ที่เกิดจากการเสียรูปเนื่องจากการหดตัว และจากนั้นตรวจสอบโดยระเบียบวิธีไฟไนต์เอเลเมนต์ ANSYS ข้อมูลจากทั้งสองโรงงาน ได้แก่ ความกว้างและตำแหน่งของร้อยแตกร้าวได้ถูกรวบรวมเพื่ออ้างอิงในการใช้แบบจำลองรอยแตกร้าวในการจำลองไฟไนต์เอลิเมนต์ โดยในการจำลองเลือกใช้แบบจำลองจากพื้นที่พื้น ที่เกิดการแตกร้าวโดยแบ่งตามรอยต่อก่อสร้างและเงื่อนไขขอบเขตการยึดรั้ง เนื่องจากพื้นที่พื้นมีขนาดใหญ่มาก ผลของความเครียดที่คำนวณได้ถูกเปรียบเทียบกับการก่อตัวของรอยแตกร้าวของงานอ้างอิง การศึกษาตัวแปรได้มุ่งเน้นที่การแตกร้าวเนื่องจากอิทธิพลของลำดับการหล่อคอนกรีต ผลกระทบของแรงเสียดทานระหว่างแผ่นพื้นและชั้นรองพื้น และผลกระทบของอัตราส่วนความยาวต่างๆของแผ่นพื้น

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Due to many advantages of slab-on-grade; especially economy and durability, they are mainly used in industries, garages and pavements for sturdy floor and in residential buildings as well. However, it is such a sensitive one in the formation of cracks mainly due to the restraint to deformation. There are possible restraints which do not allow the concrete for freely volume change; friction between slab and sub-base, the effect of piles and columns, and casting sequence.

This thesis aims to collect the data and observe the formation of cracks in slab-on-grade of two factories, mainly due to shrinkage deformation and then verify in the finite element program called ANSYS. The data from two industries, crack width and location, was collected as reference to implement cracking model in the finite element simulation. When simulated in program, the model was adopted from the cracked floor area cut by the contraction joints and the restrained boundary conditions as the floor area is very large. The output strain from the program was compared with the crack formation of reference project. The parametric study was focused on cracking which is due to the influence of casting sequence, the effect of friction between slab and subgrade, and the impact of different lengths ratio of the slab.

Department:	Civil Engineering	Student's Signature	....
Field of Study:	Civil Engineering	Advisor's Signature	....
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Chapter 1
Introduction

1.1 Background of Study

In this competitive construction business, the construction companies set their aim, to get higher reliability from the clients by fulfilling the requirements to satisfactory conditions. The clients also inspect the projects accordance with their standards. Thus it is increasing in awareness of the quality of the project from the customers, especially on concrete quality and crack problems due to mostly dealing with reinforced concrete structure. It is generally found that cracking is the main point in concrete quality control compared with other quality problems such as malfunction, corrosion, leakage and peel off.

Due to many advantages of slab-on-grade; especially economy and durability, they are mainly used in industries, garages and pavements for sturdy floor and in residential buildings as well. It is such a sensitive one in the formation of cracks in many reasons such as drying shrinkage, thermal contraction, external or internal restraint to deformation, subgrade settlement, exposed weather condition (freezing or thawing) and applied loads[1]. To say it more exactly, crack problem is mainly due to the restraint of deformation. There are possible restraints which do not allow the concrete for freely volume change; friction between slab and the sub-base, and the effect of piles and columns[2].

Moreover, when most of the concreting areas need to cast in sequences, the different temperature and deformation in slabs with different ages can behave as restraints to each other. Then, the excess moisture from the subgrade can penetrate the slab and increase slab curling, especially in slab on ground. Thus the selection of the slab thickness and well-designed vapor retarder are crucial to be sure.

The applications used in today are capable of only reducing cracks to some degree but not at all [1].Therefore, the formation of cracks cannot be prevented absolutely but the visible width can be reduced and controlled if the causes are examined and improved their influenced parameters on crack. That is the reason why researchers keep on finding the most effective solution for crack minimizing. The solutions are always desired under the simplicity (easy to do), effectiveness, few time consuming and low cost.

In this study, the slabs-on-grade of two factories will play in main roles under investigating parameters to lower cracking. The crack results of these projects will be compared with those of analysis in program called ANSYS. This analysis, especially, in shrinkage effect, the friction between slab and subgrade or vapor barrier, the effect of casting sequences of slab, will carry out the influence degree on crack formation. Therefore, the study is merely considered development of cracks that is not due to loading.

1.2 Motivation

Sometimes, the formation of cracks cannot be controlled even though the code, such as ACI Code[3], or other references are followed to treat the slab. It is on account of different countries, weather conditions, raw materials, soil conditions and other possible factors of the constructions. That is the motivation why this research was implemented under the experiment with the parameters of usual cracking control. Then, analysis will keep on chasing other parameters for the reasons of crack.

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1.3 Objectives of the Research

The main objectives of the research are as follows.

- To investigate and collect data from the reference projects
- To verify the crack model of slab accordance with restraint forces that is due to the shrinkage strain
- To analyze the different parameters in formation of cracks

1.4 Scopes

The scopes of the research as followed.

- In this research, cracks are generated from temperature load.
- Cracks after one year is considered
- Load from the external load and bearing capacity are not be considered.
- Curling effect is not included.
- Shrinkage strain is estimated from ACI-209R-92 model

1.5 Thesis Outline

This Thesis is composed by five chapters as followings.

Chapter (1) shows the introduction, overview, and objectives of the thesis.

Chapter (2) presents the literature review relating to field of thesis. It includes crack problem in concrete, cause of cracking in slab-on-grade, volume change and the restrained forces. Then the material response and behavior of concrete and reinforcing steel are also mentioned.

Chapter (3) provides the reference projects' data, including the way how to measure and collect data. Then the location and width of cracks in respective projects are also presented. In this chapter, it also mentions the prediction of shrinkage strain from ACI Code for each project.

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Chapter (4) covers the finite element implementation of the models. The finite element model is carried out according to the fundamental data of the projects. The constraints to the projects are considered as boundary conditions in the model. The measured strain from finite element models plays vital role in the chapter.

Chapter (5) includes the discussion and conclusion of the results of the thesis.

Chapter 2
Literature Review

2.1 Introduction

It is not surprising to deal with the cracks while keeping in touch with the reinforced concrete slabs. However, the formation of cracks is always undesirable due to ranging from appearance to even safety. Thus, many attempts have been done to control the cracks in slabs by many researchers. In this research, slab-on-grade in industrial floor is main character among slabs.

2.2 Crack Problem in General

Cracking in reinforced concrete can happen with regard to many causes paralleling with the age of concrete and is usual in the service stage. However, these cracks can threaten appearance, serviceability, function, and durability of the structure if the crack widths are over the reasonable limit. Moreover, through crack, water can expose to reinforcement and lead to corrosion. Although the most random cracks, such as plastic shrinkage cracks, at early age rarely impact on the design service life of the structure [4], it is not desirable and sometimes looks unsafe in the physical appearance and leads to repair which can affect large economic consequence.

To deal with the cracks in practical projects, it needs to know the cause and types of crack in nature. If the crack pattern is seen, it should be known the reason of crack. When being able to define the source of cracks, the continued propagation of cracks can be stopped to some extent and prevented for next projects. This study will focus on the types of cracks which take place not because of load but because of concrete behavior and environmental conditions, mainly on shrinkage and restraints.

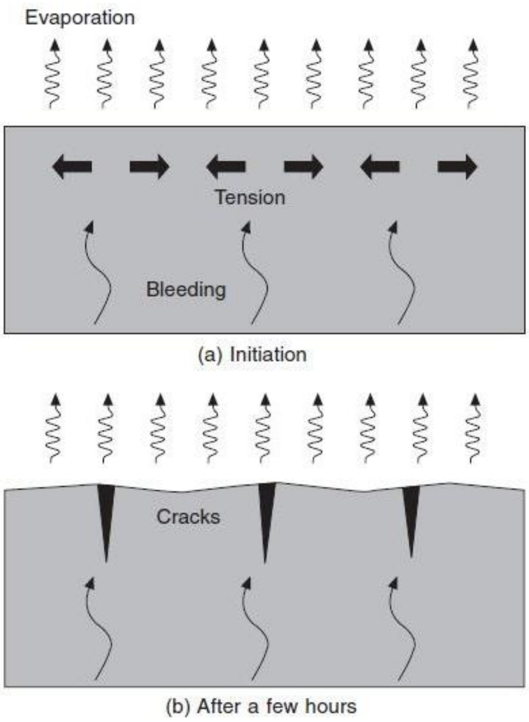

Figure 2.1:Formation of plastic shrinkage cracks (initial and final state)[5]

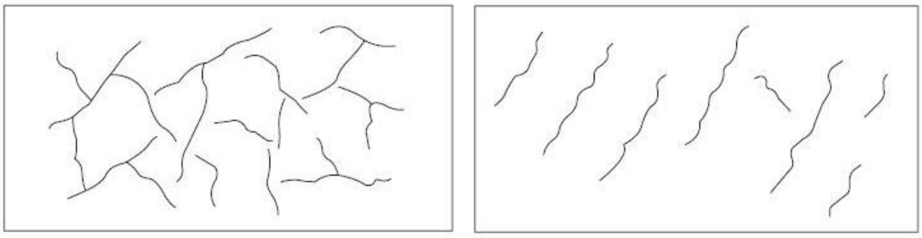

Figure 2.2: Visual appearance of plastic shrinkage cracks (map and diagonal cracking)

In generally, age of concrete can be divided into plastic stage before hardening and hardening stage. Shrinkage starts from plastic stage till to hardening stage. The usual cracking in the plastic state can be the reason of plastic shrinkage, plastic settlement and autogenous shrinkage. The plastic shrinkage can be resulted from rapid evaporation of concrete surface. Cracks appear due to different deformation which causes from varying moisture gradient between the upper and lower part of the concrete shown in Figure. 2-1. This type of crack can be formed in 30mins to 6hours after casting with diagonal or random pattern in Figure. 2-2. Plastic settlement is the cause of subsidence around reinforcements which can be the effect of surplus water in concrete mix and inadequate cover. The cracks can be formed above or along with steel bars and start 10 mins to 3 hours after placement in Figure 2-3. The autogenous shrinkage cracks might be similar with plastic shrinkage cracks and propagate with plastic shrinkage. This type of cracks is reaction of internal drying when water is consumed by the absorbent material in concrete.[6]

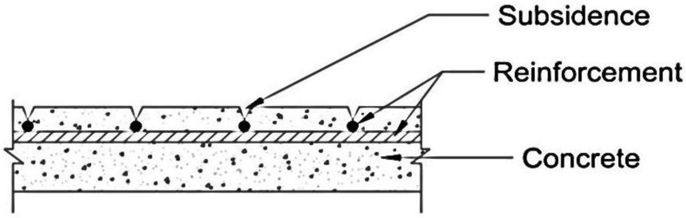

Figure 2.3: Plastic settlement cracking[6]

After hardening, cracks can happen because of the volume change in drying shrinkage and thermal alternation. Drying shrinkage is the ongoing process of concrete drying after hardening. In this case, the cracks during plastic shrinkage will keep on developing. This type of cracks may be found in transverse style Figure 2-4. They can also be seen in re-entrant corners where the stresses are concentrated due to change of dimension Figure 2-4. They can take place in weeks to years after placing. Thermal expansion or contraction can be found when heat generation or temperature changing is excessive in concrete. In this case, cracks are usually transverse and appeared in one day to three weeks.[6]

Figure 2.4: Transverse crack and re-entrant corner crack due to drying shrinkage

There are other causes of cracks such as freezing and thawing, corrosion of reinforcement, alkali-aggregate reaction, sulfate attack etc. They are not considered in this study, and the influence of volume change of concrete on cracking of concrete is kept studying in next topic.

2.3 Volume Change in Concrete

The stress induced from volume change in reinforced concrete is common cause of cracking. This volume change is mainly due to shrinkage, thermal and moisture movements (expansion or contraction)[7].

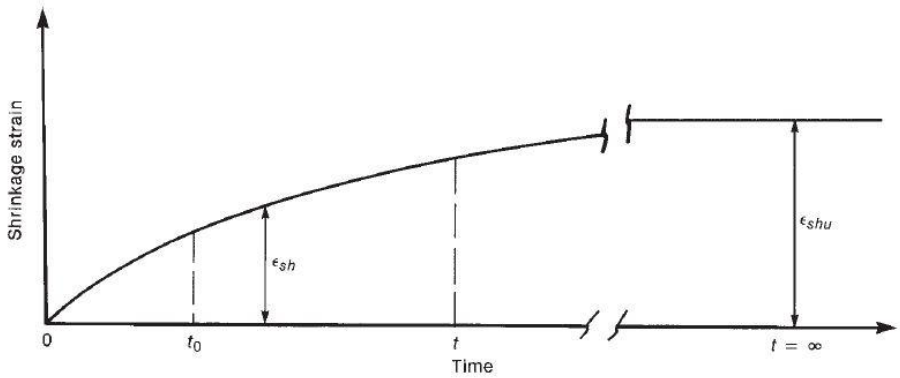

Figure 2.5: Shrinkage of an unloaded specimen [7]

Shrinkage is shrinking in hardening process of concrete under constant temperature which is the deformation or contraction in volume resulted generally from the loss of water from the concrete. In the contraction, shrinkage strains are varying with time, Figure 2.5.[7] They are influenced by relative humidity (RH) and aggregate, water and water cement ratio in concrete. The RH is the most effective one since it can control the drying rate of concrete.[8]

When there is a restraint on the concrete structure with respective shrinkage strain, it may create the tensile stress leading to shrinkage cracks because the low tensile-strain of concrete can be $150x10^{-6}$ or less[8]. Figure 2.6 [8] from ACI 224R-01 shows how shrinkage strain and restraints let the tensile stress (restraint force) crack. In order to limit rapid drying rate, curing is used as a common way as concrete can resist higher tensile strain when tensile stress is applied slowly[8].

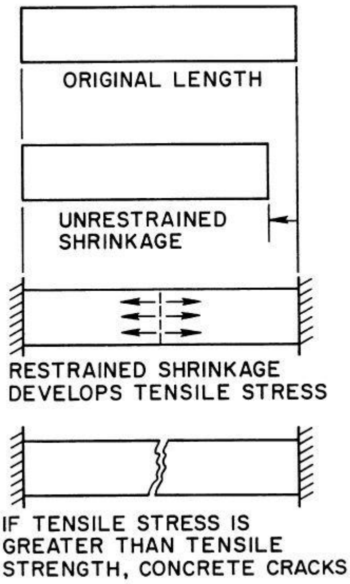

Figure 2.6: Cracking of Concrete due to shrinkage[8]

Thermal produced deformation can appear due to the fact that temperature difference throughout the concrete member is excessive. The restraints which do not let it move freely create thermal cracks. In slab, the top surface has to face with different temperature from the bottom surface.[9] So, different movements from different temperatures can be restraint to each other and then more chance to cracking. It also needs to consider temperature change between the maximum temperature at early age hydration and the minimum temperature under service in concrete because stress can happen in immature modulus of elasticity with even small amount of hydration temperature. Thus, ACI recommends the initial temperature for casting to limit between 24°C and 38°C.[10]

The coefficient of thermal expansion or contraction in concrete can be ranging over age, composition and moisture content[7] and from $5.5x10^{-6}$/°C to $14.5x10^{-6}$/°C. However, the typical thermal expansion for concrete is usually taken as $10x10^{-6}$/°C. The thermal crack patterns in slab and pavement are very similar to those of drying shrinkage, which are usually parallel to the shortest sides of the member. [9]

2.4 Causes of Crack in Slab-on-grade

The purpose of slab-on-grade is to support the applied loads by bearing on ground[11]. So it needs to be sure the compact subgrade no voids and adequate soil bearing capacity. This kind of slab is mostly found in warm climate because it can be affected by freezing and thawing in cold climate.

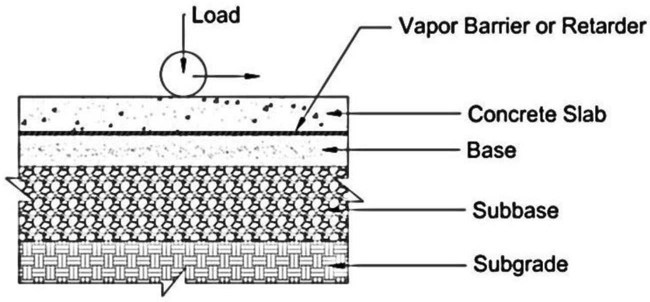

Figure 2.7: Typical design of Slab-on-grade[11]

Most of the stresses in slab-on-grade appear due to different volume changes of slab and soil, and applied loads[11]. When the restraint; subgrade or soil, prevents free movement of the concrete during shrinkage, the tensile stresses are induced and then cracking happens if this tensile stresses reach the tensile strength of concrete[8].

When it comes to slab-on-grade, curling and warping cannot be neglected since these stresses can cause to the increment of random cracking[12]. When drying shrinkage, moisture and temperature difference between the upper and lower part of slab, the curling and warping stresses are produced. Then these stresses are higher and lead to cracking. To reduce the number of enclosed construction or contraction joints where slab edges tend to curl, the shape of placing slab-on-grade panel is preferable in square shape[13].

As a result of permeability of concrete to some extent, slab can be penetrated by water and water vapor[11]. In the process, moisture goes upward to the surface for evaporation, and the bottom performs absorption from moist subgrade as in Figure 2-8. The more water slab can absorb, the higher rate of drying and shrinking happens.[6] Thus, vapor barriers are used for the purpose of prevention from penetrating water via moist subgrade. Among them, polyethylene sheeting is widely used. There is a conflict whether the slab should be cast directly on polyethylene or thin layer of sand on it. According to the references, the water cement ratio should be adjusted according to the contact one. It is because sand can absorb water from the concrete while polyethylene sheet does not let water lose from the concrete. [14]

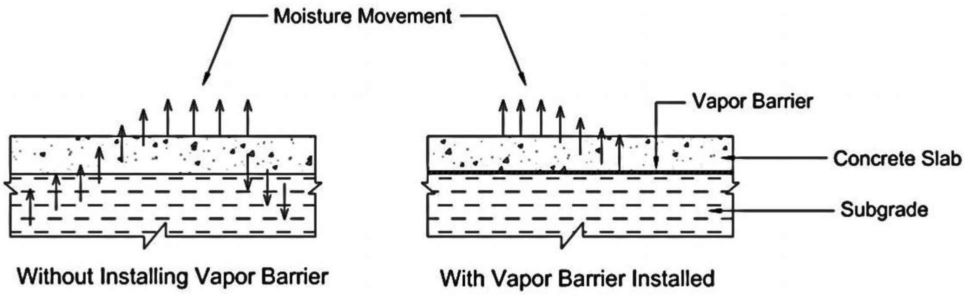

Figure 2.8 : Moisture Gradient in slab with and without vapor barrier[6]

The reasons of cracking in slab-on-grade can be controlled by design and construction basically which include not only technical factors; such as types and spacing of joints, soil-support system, method of design, concrete mixture, method for construction etc., but also human factors; such as skillful workers, feedback on evaluation of previous construction projects, etc.[11] Since it has no single technique to cover all applications, it should be designed according to the specific requirements of proposed slabs[11].

There are possible ways to prevent cracking; slab with distributed reinforcement, shrinkage-compensation concrete, post-tensioning concrete and removing restraints to freely deformation[11].To control the crack, the particle way is to design the joints (construction, contraction and expansion joints) on slabs since shrinkage cracks usually occur about every 4.572m[13]. These saw Joints are also a type of cracks which is created by designers to make the weakest portion in the slab.

On the other hand, maximizing the joint spacing is favorable in industrial floor due to the expense of joint spalling resulted from heavy load or vehicle’s wheels. To achieve this, the distributed reinforcement in upper half of a slab can be applied because it can reduce the required number of joints and shrinkage cracking[13]. The reinforcement ratio need to install at least 0.15% distributed reinforcement in the upper half of slab where occurs the highest shrinkage[13]. The main performance of distributed reinforcement is to limit the crack width resulting from shrinkage and temperature restraint, and applied loads[11]. It can also let the narrow cracks to some degree in the early stage as internal restraint.

2.5 Restraint Force

The restraint force is the conflict between movement and prevention to some extent in two structures. Cutting or removing the restraint degree is also one way to reduce cracking[13]. They can be the cause of internal and external restraints in concrete member[2]. The internal restraint can result from aggregate size which does not permit concrete from hardening, the reinforcement that does not have the same deformation degree with concrete, and the moisture gradients which need different movement. The external restraints can be pile, subgrade, foundation and contact members.

The external and internal restraint of drying shrinkage needs different approaches. The external restraint, V/S (volume surface ratio) is small, takes account of reinforcement design in controlling cracks.[10] With the regard to controlling cracks, the minimum reinforcement percentage is between 0.18 and 0.2%.[8] The internal restraint in drying shrinkage with large V/S creates the surface cracks extending a short distance to the inner part. This crack patterns are so small and have no effectiveness by reinforcement. Using reinforcement is also no influence in plastic cracking.[10]

According to the restraint degree, R, it can be calculated how much degree is prevented to move in Eq-(2.5) and, generally, restraint cases can be no restraint (R=0), partially restraint (0<R<1) and fully restraint (R=1)[2].

$$R = \frac{actual\ restraint\ force}{restraint\ force\ in\ case of\ full\ restraint} \qquad Eq\ 2.1$$

The frictions under slab on ground can be soil subgrade and vapor barrier. It is also one kind of constraint cases. This restraint depends on the friction coefficient and

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area of contact subbase[11]. The coefficient of friction can vary according to the touched elements, for instance, vapor barrier.

The procedure of casting is dealing with the restraint forces to shrinkage and thermal volume change, too. In ACI 302.1R, the recommended placing sequence is long-strip construction in which contraction joints are placed transversely. The checkerboard sequence are not recommended to use because of difficult and expansive access[1]. In the research of Al-Gburi, M. team [15], with regards to his analysis, long contact area followed continuous casting had the same restraint and the jump casting between two old concretes is the worst technique.

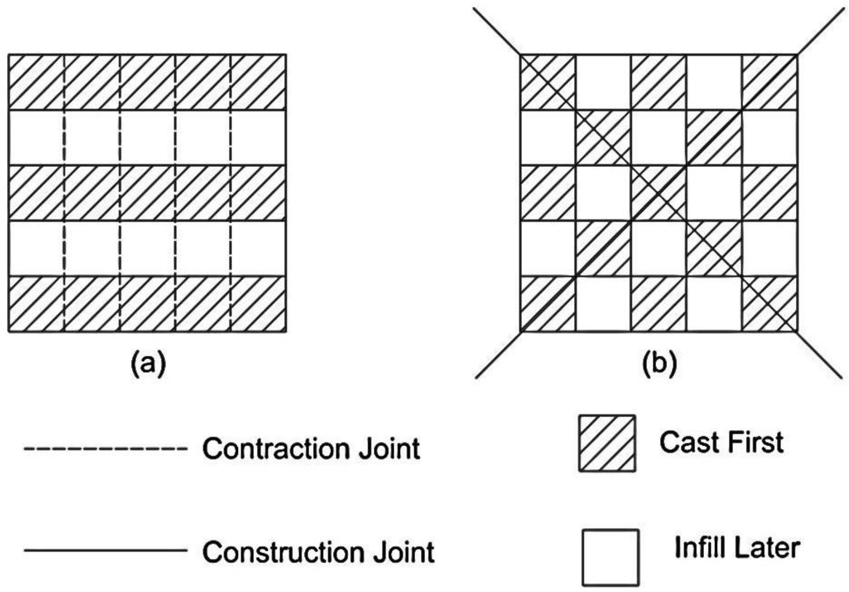

Figure 2.9: Placing Sequences Recommended and not Recompensed in ACI; (a) Long Strip Construction and (b) Checkerboard Construction[1]

2.6 Material Behavior

2.6.1 Concrete

Concrete has very different behavior in compression and tension cases. It has a quasi-brittle or strain softening failure mode with low fracture toughness. Normally, the tensile strength is only one tenth of the compressive strength. [16]

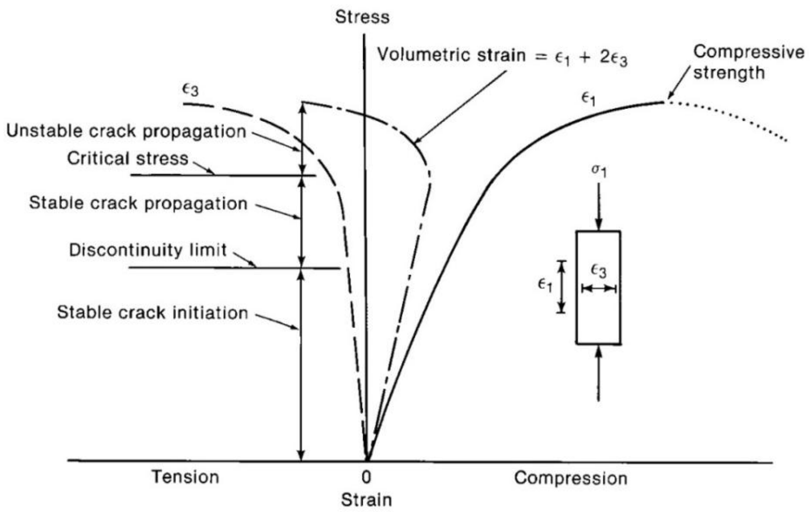

Figure 2.10: Stress-strain curves for concrete loaded in uniaxial compression[7]

The typical stress-strain curve of the concrete is the combination of linear and nonlinear part under uniaxial compressive strength in Figure 2-10.The linear part is up to 30 % of the ultimate strength, in which no-load bond crack can be occurred due to the restraint between shrinkage of cement paste and aggregate. Above 30-40% of the maximum compressive strength, the onset of bond cracks is formed before the motor crack initiate at 50 or 60%. This stage, motor cracks are only propagated with the increased load, is called discontinuity limit. At 75 to 80% of ultimate strength, motor cracks paralleling with the compressive load are continuously formed until the concrete fails. The beginning of cracking in this stage is termed critical stress.[7]

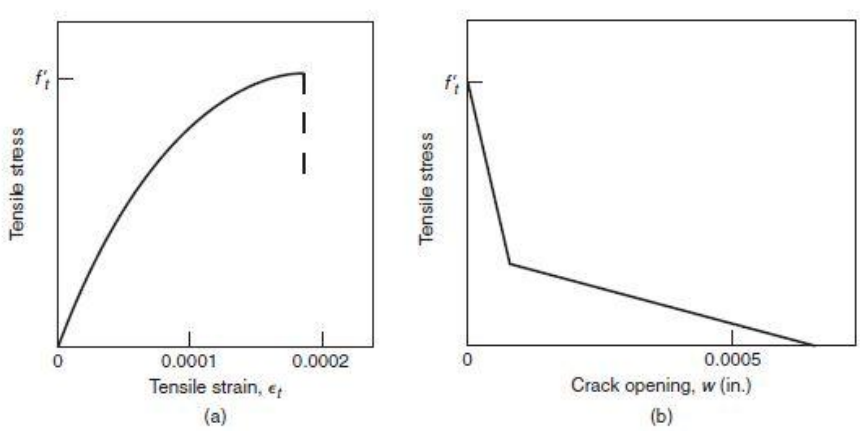

Figure 2.11: Stress-Strain curve and stress-crack opening curves for concrete loaded in tension[7]

Under uniaxial tensile load, the stress-strain curve is parabolic before it reaches ultimate strength in Figure 2.11. The stage of crack formation and crack width can be found in Figure 2.11.

While reaching the maximum tensile strength of concrete, micro cracks are found in fracture process zone and tensile strength in concrete fall suddenly. Then, these micro cracks bridge between each other in Figure 2.12(c).After bridging, these cracks cannot transfer larger stress and lead to larger crack width in Figure 2.12(d). When the crack opens completely, there is no longer tensile strength in concrete in Figure 2.12(e) .[7, 17]

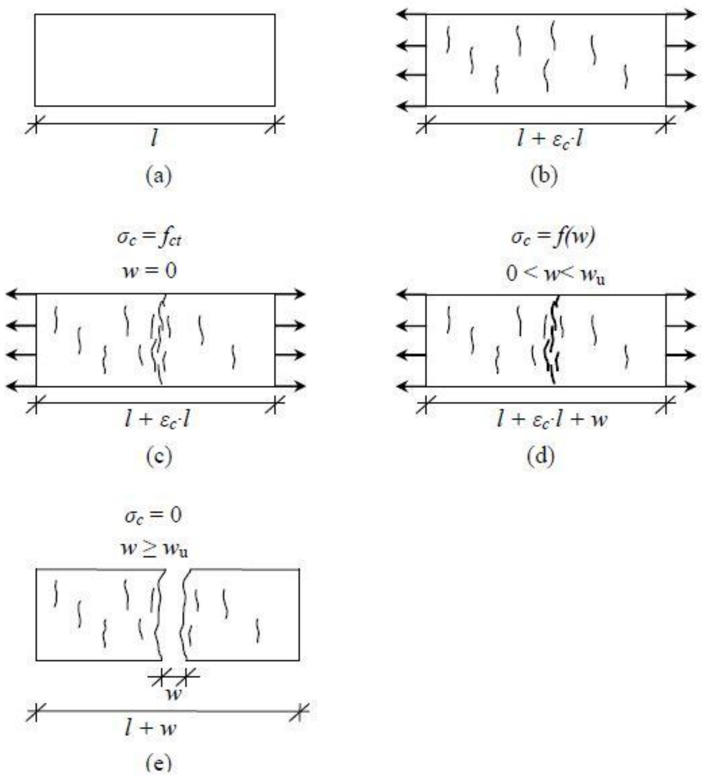

Figure 2.12: Fracture development of a concrete specimen subjected to tension till failure Based on [17, 18]

2.6.2 Failure Criteria for Concrete in ANSYS

In ANSYS, the failure of concrete can be predicted in both cracking in tension face and crushing in compression. To operate these two failure modes, the two input parameters called ultimate uniaxial tensile and compressive strength are required to define. The mulilinear stress-strain curve is used to represent the behavior of concrete compression. Figure 2-13 shows the 3-dimensioanl failure surface for concrete. The three failure projections are presented as the on σxp- σyp plane, which are σzp >0, σzp =0, and σzp <0. As the mode of material failure is a function of the sign of σzp, if σxp and σyp are both negative and σzp is slightly positive, cracking would be predicted in a direction perpendicular to the σzp direction, and if σzp is zero or slightly negative, the material is assumed to crush. [19]

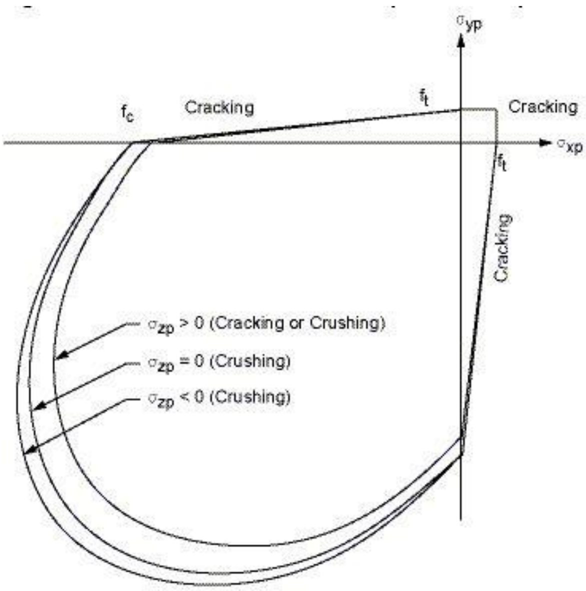

Figure 2.13: Failure Surface for concrete in ANSYS[19]

Cracking can happen whenever the principal stress in any direction reaches the outside of the failure surface. This means that crack can occur when the principal tensile stress is beyond the strength of concrete. In ANSYS, the smeared cracked pattern can be seen at the integration point or in the centroid of each element.

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2.6.3 Reinforcing Steel

Figure 2-14 (a) shows the typical behavior of steel in stress-strain curve for uniaxial loading. In the figure, the curve begins in linear shape with the initial tangent modulus of elasticity before it gets to yield point. This modulus of elasticity, E_s, is adopted as 200,000 MPa ($29x10^6$ psi) for all reinforcing steels [7]. Then, the curve goes on with strain hardening region until it reaches the ultimate tensile strength. After that, it becomes flat and leads to failure. However, it is usually assumed the behavior of steel in design as the bilinear elastic-plastic material which is same in tension and compression as shown in Figure 2-14 (b). [20] In the analysis, only the small load such as temperature will affect to the reinforcement and thus the elastic range can cover for the models.

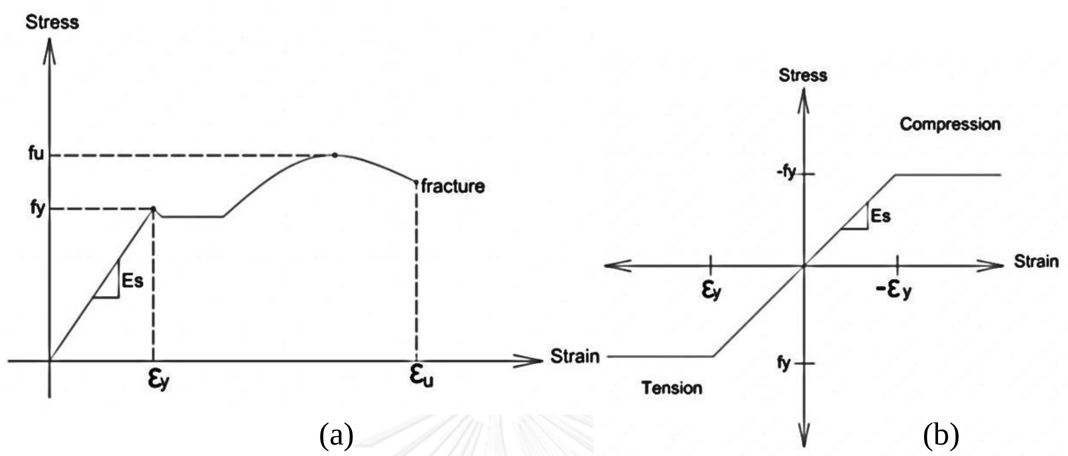

Figure 2.14: (a) Typical Stress-Strain Curve for Behavior of Reinforcing Steel And (b) Stress-Strain Curve of Reinforcing Steel in Design[20]

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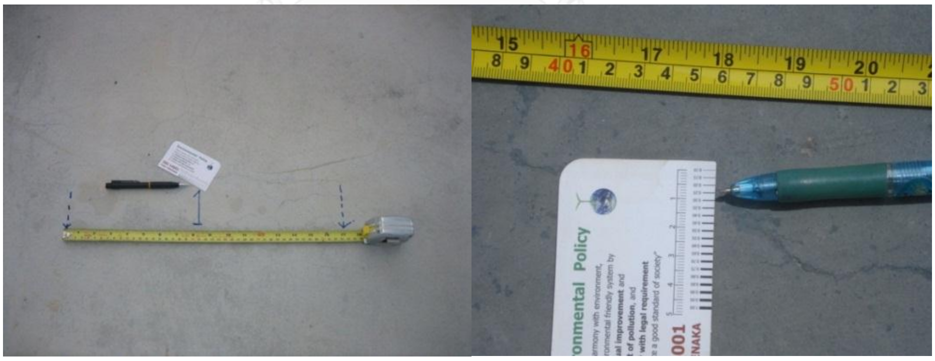
Chapter 3
Observed Data of Reference Projects

3.1 Introduction

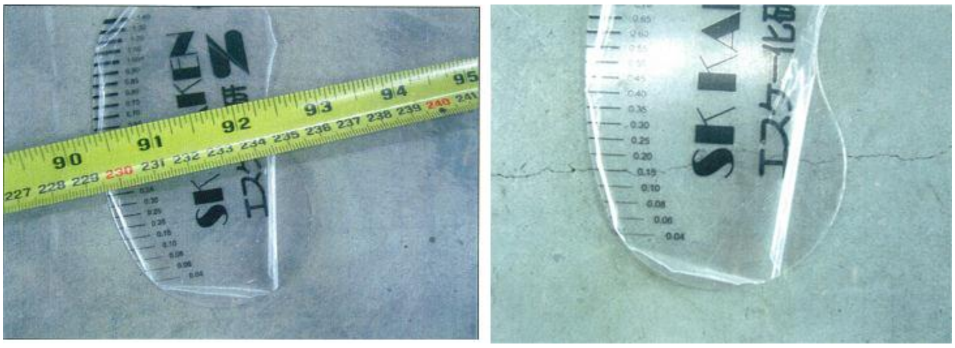
In this chapter, the observation of cracks formation, location and patterns on slabs-on- ground of two factories are shown and discussed.

3.2 How to measure

In this study, the crack formation in slab-on-grade is observed in two industries. Then it is intended to compare the propagated cracks and collected data from factories with the implementations from finite element analysis. As the floor area is so large, it is just only considered the specific area of crack formation or joint cutting area. According to the location and pattern of cracks, it is examined causes and problems, and then introduced to the program. For example, the reasons of cracks can be restraints and temperature difference. These projects are situated in Thailand.



(a)



(b)

Figure 3.1: Inspection of crack width and length in slab-on-grade of the Projects

The measurements of these projects were executed in 6 months to 1 year after casting. The data collecting activities includes measuring crack length and width, taking photos and recording the location of cracks in floor plan. In Figure 3.1, it shows how to measure crack width and length in practical. The collected data is very limited since the project is very large and not under control like experiment.

The detail design of the slab such as cross-section of slab, planning of joints and floor plan get directly from the related design department of the projects. Other necessary points could be known by interviewing respective person of these projects.

The evaluation of the project to notice the condition of crack formation directly was carried out by crack index as follow in Eq-(3.1),

$$Crack\ Index = \frac{sum(\,W \times L)}{A} \qquad \textit{Eq 3.1}$$

Where W= width of crack (cm),

L=length of crack (cm)

A=total area of measure (m^2).

It is empirical equation in which the widths and lengths of the crack are measured and recorded visually in different months. By means of the equation, the crack index is directly proportional to the amount of crack formation in floor area. From this equation, it can be compared easily the amount of narrow crack and wider crack happening in the project.

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3.3 Reference Projects Observation

The project contractors have willing to reduce or minimize the formation of early cracks in these projects. Therefore, they examine and discuss in step-by-step approaches such as design, construction method, material and mixing. In design and planning, they controlled the reinforcement ratio and the joints in square shape as shown in Table 3-1. The square shape of joint cutting area is the best to withstand cracking[21]. The projects were also introduced the construction processes such as improving the reinforcement around columns and taking care water curing days and procedure. Checking mix design and water content in concrete were carried out to ensure that no cracks happen due to surplus of water.

All of the projects are reinforced concrete and steel structure factories. Table 3.2 shows the general conditions of the three projects observed. As shown in Figure 3-2, the slab edge near the ground beam rests on it so that loose soil around the beam or footing cannot harm the slab with different settlements. On the other hand, this touched ground beam can behave as the restraint in slab concrete deformation. Another part of the slabs is fully bearing on the ground that means transferring the entire suffered load of slab to the ground. The symbols used in slab floor plan of the projects can be seen in Figure 3.3.

Table 3.1:Parameters Introduced to the Projects

Items	Parameters
Reinforcement Ratio	> 0.2%
Water Curing	7 days
Cutting Joint Time	within 2 days
Contraction Joint Interval	@ 6 - 10 m or less (L/W<1.2)
Construction Joint Interval	< 20m (L/W<1.2)
Depth of Joint	25mm

Table 3.2 : General data of observed projects

Project	Slab Thickness (mm)	Floor Area (m2)	Construction Joint Cutting (mm x mm)	Contraction Joint Cutting (mm x mm)	Compressive Strength (MPa)	Yield Strength of Reinforcement (Mpa)
A	180	7488	10,000x18,000	5000x9000	21	420
B	150-200	1782	12,000x24,000	6000x6000	21	420

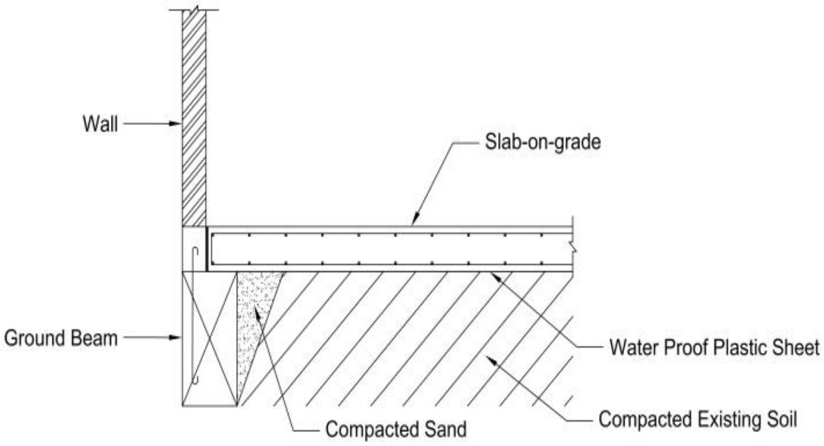

Figure 3.2 : Cross-Section of Slab at the Edge or Near Ground Beam

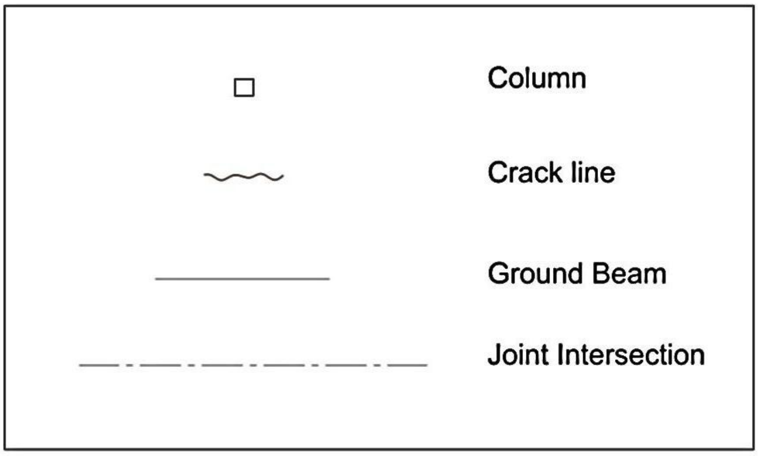

Figure 3.3: Indications Used in the Slab Floor Plan

3.4 Project-A

Project-A is a floor of an industrial building having the area of about 7400m^2. The location of cracks in floor plan can be seen in Figure 3-5 and their width and length in Table-3.3. Contraction joints show as a grid line in the floor plan. The steel and slab design for all area is same in this project. The detail section of slab can be seen in Figure 3.4. As shown Figure, the covers are 30mm and D12 bar at 200mm is used for reinforcement. In accordance with working experience, the slabs are found more cracks when the spacing of reinforcement and upper cover distance are lower than above limits. In this project, the casting procedure is not available.

Table 3.3: Widths and Lengths of the Cracks

Crack Point	Width (mm)	Length (mm)
1	0.4	1900
2	0.2	2300
3	0.15	1640
4	0.15	1750

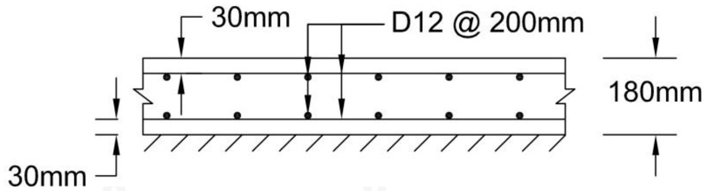

Figure 3.4: Cross-Section Detail and Reinforcement of Slab in Project-A

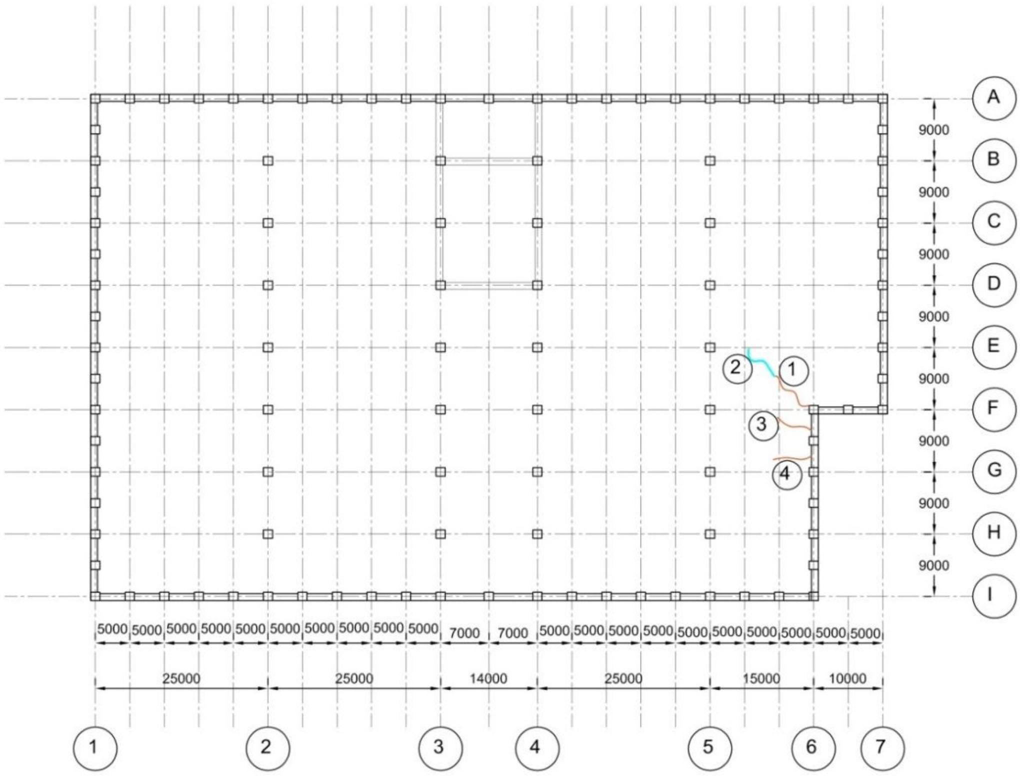

Figure 3.5: Location of Cracks in Floor Plan of Project-A

3.4.1 Observation

In this project, only four crack lines which start from the beam and column are found. The width of the crack is ranging from 0.15 to 0.4mm. The crack line (1) starts from the column with the width of 0.4mm and then propagates to crack line (2) after 1900mm with the width of 0.2mm. Figure 3-6 shows how to measure crack point-1 of the project.

According to the evaluation of the empirical equation (Eq-3.1) in Table 3-4, 0.15mm width of crack and the cracks greater than 0.3mm have same crack index less than 0.005. This means that they have the same amount of cracks formation with respect to the area.

Table 3.4: Crack Index in Project-A

Project	Crack Index (cm2/m2)	Width of Crack (mm)
Project-A	< 0.005	0.15
	< 0.005	≥0.3

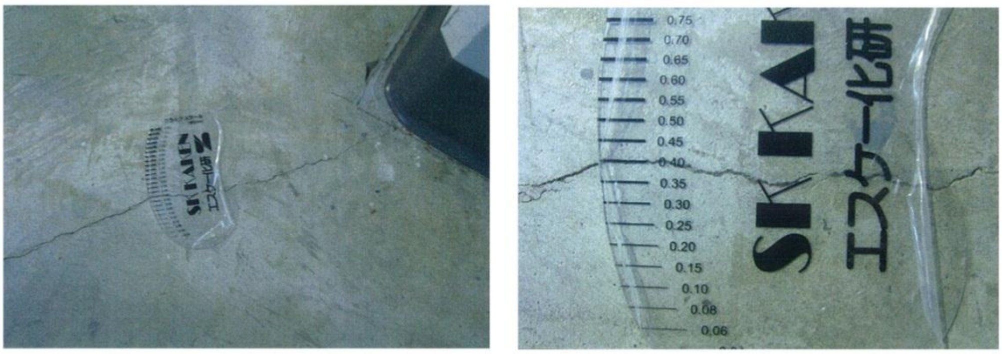

Figure 3.6: Crack Point-1 of Project-A

3.5 Project-B

Project-B is also slab-on-grade of a factory with 1782m^2 floor area. The location and width of the cracks in this project can be seen in Figure-3.8 and Table-3.5. In Figure 3.8, different hatch patterns show different design procedures such as reinforcement and thickness in order to the demands of different live load cases. The slab before casting can be seen in Figure 3.7.

Figure 3.7: Slab-on-grade of Project- B under the Construction

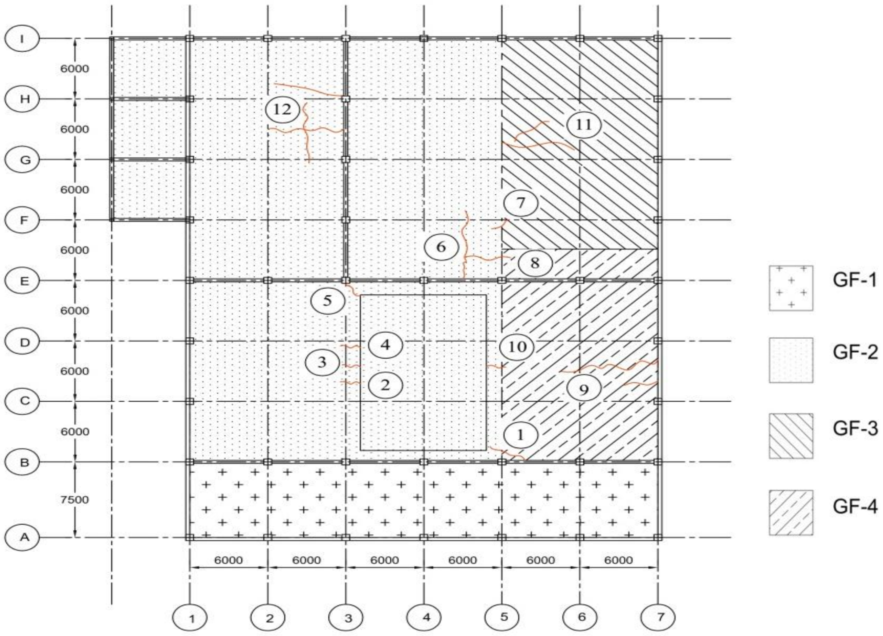

Figure 3.8: Location of cracks in floor plan in Project-B

Table 3.5: Width and Length of Crack Point

Crack Point	Width (mm)	Length (mm)
1	0.08	2,000
2	0.06	1,500
3	0.08	1,500
4	0.06	1,500
5	0.55	1,800
6	0.2	6,500
7	0.2	4,000
8	0.15	4,000
9	0.2	8,500
10	0.15	1,500
11	0.04	9,000
12	0.15	8,000

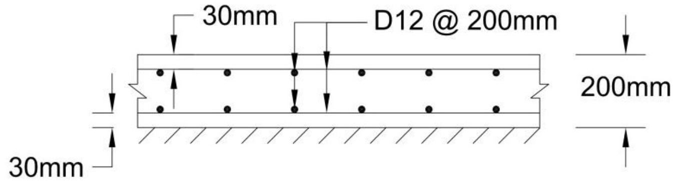

Figure 3.9: Detail Cross-Section and Reinforcement of GF-4 Slab

Figure 3-9 shows detail cross-section and reinforcement of GF-4 type slab and other kinds of slabs can be seen in appendix for detail. Generally the reinforcement installation is two layers and used bar D12 in 200 mm spacing. The casting procedure can be seen in Figure 3.10.

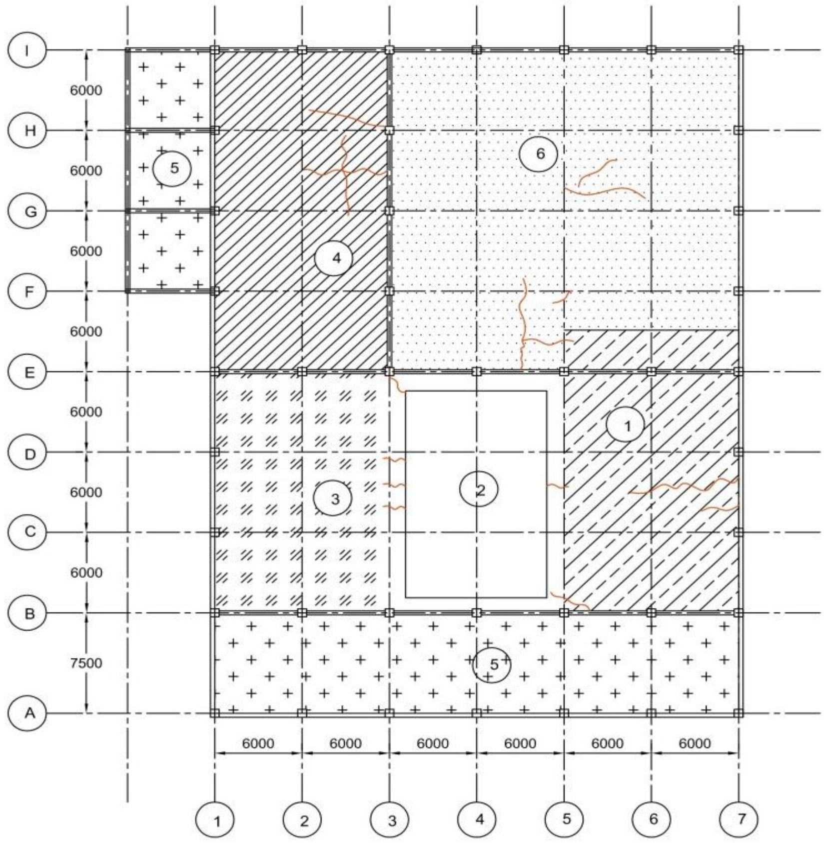

Figure 3.10: Casting Sequence of Project-B

3.5.1 Observation

When compared to project A, project B has recorded more amount of cracks although it got same treatments such as water curing, joint cutting day and joint interval controlling. With regard to the crack location in floor plan (Figure 3.8), it is found that most of the cracks come from the restrained members such as walls and ground beams. The other cracks also come from adjacent slabs of different casting time. The widths of crack are ranging from 0.04 to 0.55 mm. Figure 3.11 shows the measurement of crack point 9 and 8. In Table 3-6, it shows the crack index value in project-B. The crack width 0.15mm has much more amount of crack formation than the crack width of 0.3mm.

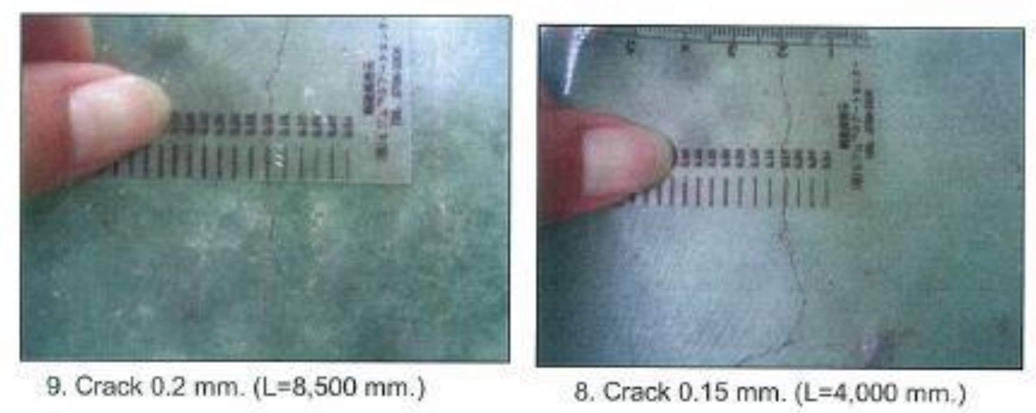

Figure 3.11: The Measurement of Crack Point No.9 and No.8

Table 3.6 : Crack Index in Project- B

Project	Crack Index (cm2/m2)	Width of Crack (mm)
Project-B	< 0.03	0.15
	< 0.01	≥0.3

3.6 Estimation of Total Shrinkage and Thermal strain

As mention in chapter (2), the shrinkage and thermal strain play vital roles in volume change which has influence on crack width. Therefore, it needs to determine shrinkage and thermal strain.

In estimation of shrinkage strain, ACI 209R-92 model is used in this study because the observed project is the constructed factory in the field and not under control. This model is recommended by ACI Committee 209 and is an empirical model. The prediction of shrinkage strain is the function of time which is in hyperbolic curve. This shape of curve relies on the conditions such as curing, mixture design, ambient temperature and humidity. In the method approached for prediction, the ultimate standard value is applied by correction factors. [22] This method generally requires the followings.

- Age of concrete after curing
- Curing method

- Relative humidity
- Volume-surface ratio
- Content of fine aggregate percentage
- Cement content
- Air content in percentage
- Cement type

According to the comparison of the calculated and measured shrinkages strain, it shows that this model overestimates the shrinkage strain in short drying times and underestimates in long drying time.

As mentioned above, the relative humidity (RH) influence on shrinkage strain and it becomes largest when RH is equal or fewer than 40 %. The shrinkage strain equation is the function of concrete age t(day) and curing age t_c(day) in Eq 3.2. The ultimate strain in the equation is multiplied by the seven correction factors of different parameters. The calculation is carried out as the following procedure. Figure 3-12 shows the sample shrinkage strain in ACI-209.[7, 22]

$$\varepsilon_{sh}(t,t_c) = \frac{(t-t_c)}{35+(t-t_c)}(\varepsilon_{sh})_u \qquad \textit{Eq 3.2}$$

Where, $\varepsilon_{sh}(t,t_c)$ = shrinkage strain after t_c days

$(\varepsilon_{sh})_u$ = ultimate shrinkage strain at 40% RH = 780×10^{-6}

$$(\varepsilon_{sh})_u = 780 \times 10^{-6} \times \gamma_{sh} \qquad \textit{Eq 3.3}$$

$$\gamma_{sh} = \gamma_{tc} \times \gamma_{RH} \times \gamma_{vs} \times \gamma_s \times \gamma_\varphi \times \gamma_c \times \gamma_\alpha \qquad \textit{Eq 3.4}$$

Where,

γ_{tc} = Moisture curing correction factor

γ_{RH} = *Relative humidity coefficient*

γ_{vs} = Volume-to surface ratio factor

γ_s = Slump of fresh concrete factor

γ_Ψ = Fine aggregate factor

γ_c = Cement Content factor

γ_α = Air content factor

$\gamma_{tc} = 1.202 - 0.233 log(t_c)$ *Eq 3.5*

For $40\% \leq RH \leq 80\% \rightarrow \gamma_{RH} = 1.40 - 0.01 \times RH$ *Eq 3.6*
For $RH > 80\% \rightarrow \gamma_{RH} = 3.00 - 0.03 \times RH$ *Eq 3.7*

$\gamma_{vs} = 1.2^{-0.12V/S}$ *Eq 3.8*

$\gamma_s = 0.89 + 0.00161\, s$ *Eq 3.9*

If $\psi \leq 50\% \rightarrow \gamma_{\varphi} = 0.30 + 0.014\, \varphi$ *Eq 3.10*

If $\psi > 50\% \rightarrow \gamma_{\varphi} = 0.90 + 0.002\, \varphi$ *Eq 3.11*

$\gamma_c = 0.075 + 0.00061\, c$ Eq 3.12
$\gamma_\alpha = 0.95 + 0.008\alpha \geq 1$ Eq 3.13

Where,
t_c = Curing period (days)
RH = Relative Humidity in decimal
V/S = Volume surface ratio (mm)
s = Slump (mm)
ψ = Ratio of fine aggregate to total aggregate (%)
c = Cement content (kg/m^3)
α = Air Content in Content (%)

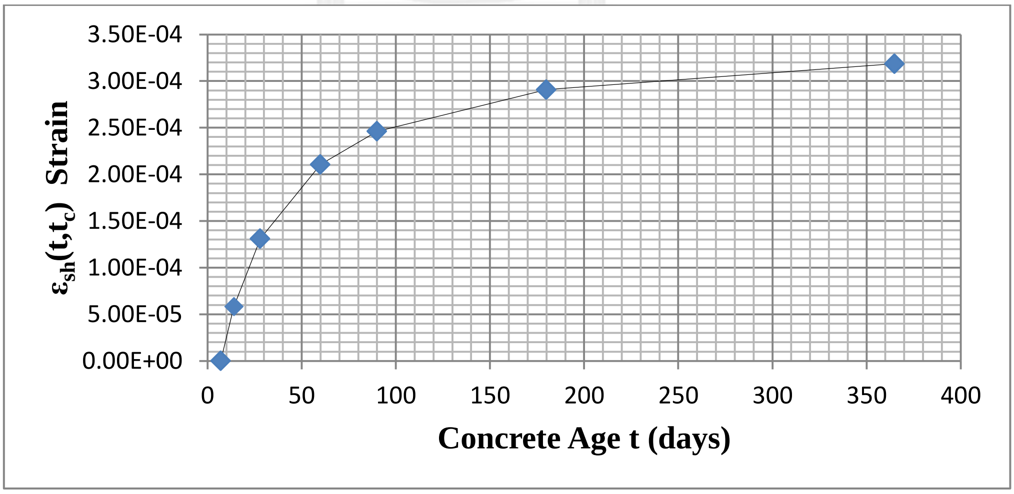

Figure 3.12: Sample of Shrinkage Strain Predictions

For the estimation of thermal strain, the maximum and minimum temperature of concrete needs to know, but, in this real project, it is difficult to know the exact one. Thus, corresponding to the assumption of reference [23], the maximum temperature of concrete is taken with respect to the ambient temperature and the minimum temperature as zero degree Celsius. The general ambient temperature in Thailand is 30° C. In this way, the total temperature change is 30° C (30-0). When multiplying this temperature with coefficient of thermal expansion, the possible thermal strain can be defined in 300με.

$$\textit{Total shrinkage and thermal strain,}\varepsilon_{sh+th} = \varepsilon_{sh}(t, t_c) + 300\mu \qquad \textit{Eq 3.14}$$

3.6.1 Evaluation of Shrinkage Strain for Project-A and B

The shrinkage strain prediction is in Figure 3-13 and Figure 3-14. The mix design of projects and calculation procedure of Figures can be seen in appendix. Since the project data collection was carried out one year after casting of slab, the shrinkage strain at 365 days is considered to calculate the total shrinkage and thermal strain, ε_{sh+th} which is as follow.

For Project-A,

When t=365days and tc=7 days, $\varepsilon_{sh}(t, t_c) = 464\mu$

$$\varepsilon_{sh+th} = 464\mu + 300\mu = 764\mu$$

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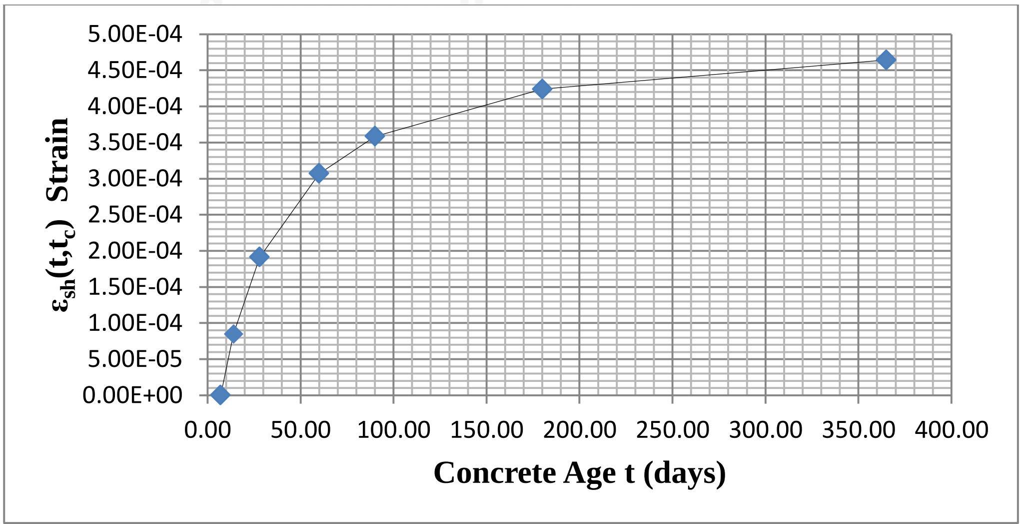

Figure 3.13: Shrinkage Strain Prediction for Project-A

For Project-B,

When t=365days and t_c=7 days, $\varepsilon_{sh}(t, t_c) = 443\mu$

$$\varepsilon_{sh+th} = 443\mu + 300\mu = 743\mu$$

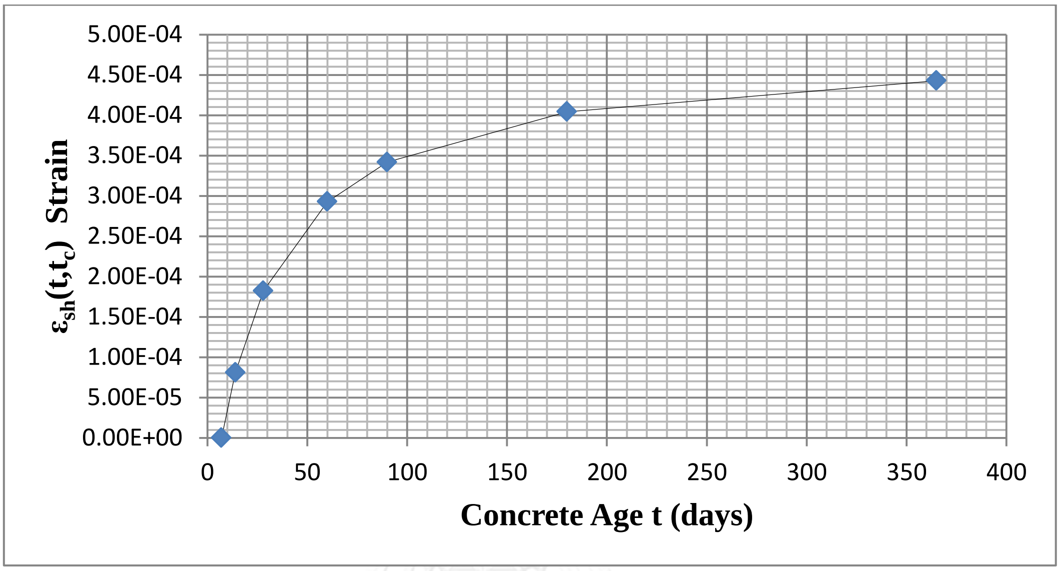

Figure 3.14: Shrinkage Strain Prediction for Project-B

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Chapter 4
Finite Element Simulation

4.1 Finite Element Program

The proposed model is simulated in the finite element software ANSYS13.0 which is widely used to simulate both linear and nonlinear analysis.

4.2 Geometry of Model

The geometry of slab is adopted from the real slab of the project. As the slab is very large to model in program, the specific slab area cut by contraction joint line where the crack occurs is simulated. This means that according to the layout of construction joints, length and width of the slab will be adopted. Depth and cover are same with respective projects and the general geometry of slab is in Figure 4.1. In Figure 4-2 shows the model in ANSYS.

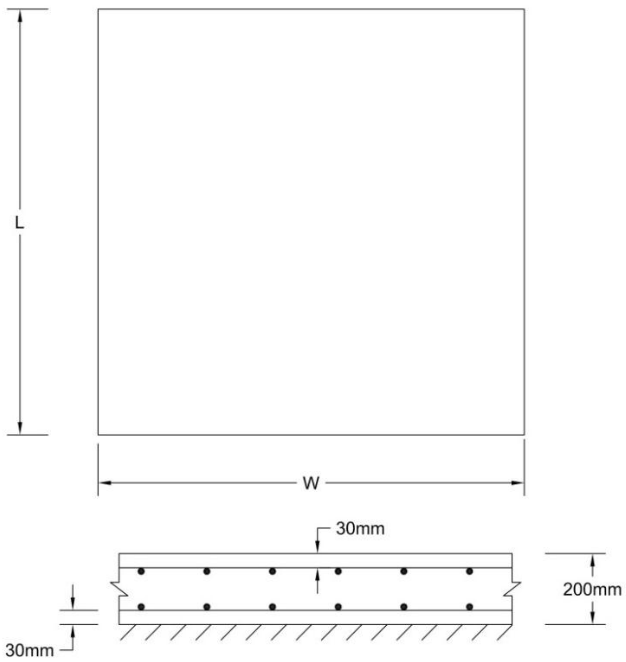

Figure 4.1: Geometry of Slab-on-grade in Project

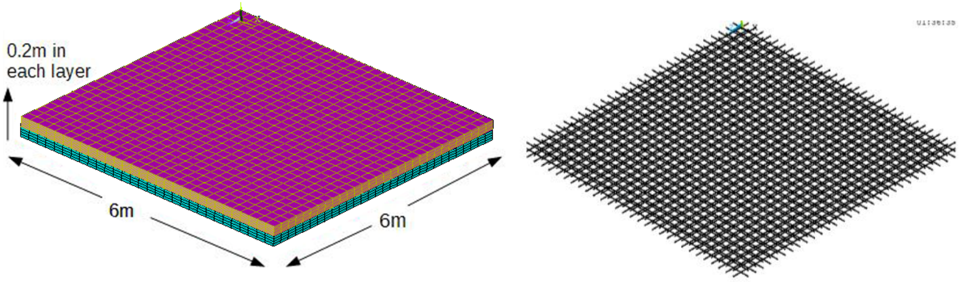

Figure 4.2: Modelling and Meshing of Slab (upper), Subgrade (lower) and Reinforcement in Program

4.3 Material Model

4.3.1 Concrete

In the research, solid65 element in ANSYS program will be used as a concrete model which is for 3D modeling of solid with reinforcement or without reinforcement in Figure 4-3. This model is 8 nodes brick elements with three degrees of freedom per node; translation in x,y,z directions. This element has nonlinear properties which are available for cracking in three orthogonal directions, crushing, plastic deformation and creep.[19]

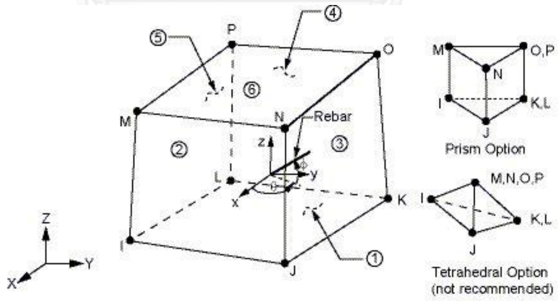

Figure 4.3: Solid65 Geometry [19]

The modeling of reinforced concrete in this research is based on reference [24] and [25]. The uniaxial stress-strain relationship in compression of concrete is represented as a multilinear isotropic curve as shown in Figure 4-4 and the following Eqs- 4.15 to 4.17 are used to implement this curve[24, 25]. After the limit of elasticity, $0.3f_c$', the multilinear curve before the peak compressive stress is the work hardening stage of behavior, and then plastic response is presumed to happen when it reaches the peak compressive stress[26].

$$f = \frac{E_c\,\varepsilon}{1+\left(\frac{\varepsilon}{\varepsilon_0}\right)^2} \qquad \textit{Eq 4.1}$$

$$\varepsilon_0 = \frac{2f_c}{E_c} \qquad \textit{Eq 4.2}$$

$$E_c = \frac{f}{\varepsilon} \qquad \textit{Eq 4.3}$$

Where, f=stress at any strain ε, MPa

ε = strain at stress f

E_c= concrete elastic modulus, MPa

ε_0 =strain at the ultimate compressive strength, f_c'

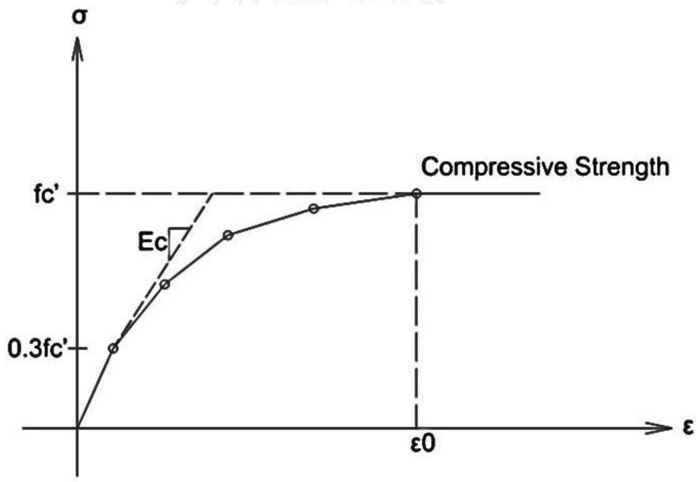

Figure 4.4 : Uniaxial Stress-Strain Curve for concrete in compression[24, 25]

Solid65 will approach the nonlinear behavior of concrete using smeared crack approached[24]. For the tension side of concrete, the maximum tensile strength of concrete or modulus of rupture will be calculated from ACI code section 9.5.2.3[3] in Eq 4.18. The crack face condition ranging from smooth (complete loss of shear transfer) to rough (no loss of shear transfer) for open crack is represented as shear transfer coefficient, β_t in ANSYS. The value of β_t less than 0.2 has found in convergence problem [27]. The assumption of β_t follows the reference [25]. The shear transfer coefficient in closed crack is taken 1 which means the shear stiffness reduction in model is fixed to zero[27].The uniaxial crushing stress is set to -1 which default meaning in ANSYS program is removing the crushing capability[19]. The required inputs in ANSYS programs such as the modulus of elasticity of concrete is calculated from ACI code section 8.5.1[3] and the typical poisson's ratio is take as 0.2.

$$f_r = 0.62\lambda\sqrt{f_c'} \qquad \textit{Eq 4.4}$$

$$E_c = 4700\sqrt{f_c'} \qquad \textit{Eq 4.5}$$

Where, f_r= modulus of rupture or maximum tensile strength of concrete (MPa)

λ = 1 for normal weight concrete

f_c'= concrete compressive strength(MPa)

E_c(EX) = the modulus elasticity of concrete (MPa)

μ(PRXY)= poisson's ratio

4.3.2 Reinforcement

Link180 element will be implemented as reinforcement in this model. This element is truss element behavior; uniaxial tension-compression element with three degrees of freedom at each node; translation in x, y and z direction in Figure 4.5[19]. Bilinear isotropic materiel based on Von Mises failure criteria is the assumption of material behavior of reinforcement as the reference [25]. In the consideration of bond between concrete and reinforcement, the two materials will share same node at the location of reinforcement in order to construct the perfect bond as assumption[27]. The input data for the reinforcement is taken as typical values and the yield strength is from the project.

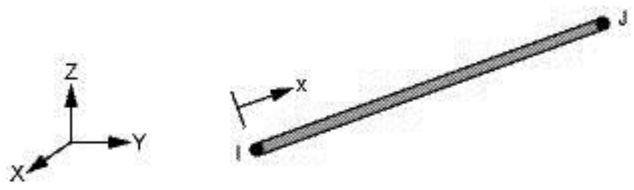

Figure 4.5: Geometry of Link180 [19]

Input Data for reinforcing steel,

E_s =modulus of elasticity of steel

μ(PRXY) = poisson's ratio

f_y = yield stress of steel

4.3.3 Subgrade or soil

In ANSYS, the option which approaches the Drucker-Prager constitutive law is used to apply to granular (frictional) material such as soils, rock, and concrete. It is also used in reference [28] to represent the soil model. In this study, this option is used with solid65 to model the subgrade. Three inputs need to approach this material; the cohesion value (must be > 0), the angle of internal friction and the dilatancy angle.

To put the required input to the soil model, the related basic data from the projects is taken. In projects, the average standard penetration test (N value) is 11 and soil type is Calyey sands soil. According to this data, from Geotechdata website [29], the data for the angle of internal friction and cohesion value are adopted and applied in the program.

To model the connection between slab and subgrade, the contact element in ANSYS (CONTAC174 and TARGE170) is used. This element with eight nodes represents contact and sliding between three dimensions target and deformable surface. The friction in this model can be controlled by the coefficient of friction (MU). The behavior of contact surface can be adjustable in KEYOPT(12). The contact element performs to transfer load from the footing to soil and also generate friction between the contact members.

4.4 Load, Boundary Conditions

The understanding of drying shrinkage is initial deformation or strain subjected to member. The simulation of shrinkage in the thesis is introduced as equivalent temperature which is converted from free shrinkage strain in Eq 4.20 [23, 25].

$$\Delta T = \frac{\varepsilon_{free}}{\alpha} \qquad Eq\ 4.6$$

Where, ΔT=equivalent shrinkage temperature (°C)

ε_{free}=free shrinkage strain

α = the coefficient of thermal expansion of concrete = 10×10^{-6}/°C

In the analysis, the decrease of equivalent temperature will be applied to the whole model. Seeing that shrinkage strain will not happen in the reinforcement, the assumption will take zero for the coefficient of thermal expansion for steel.[17] Different expansion of them under decreasing temperatures can be one reason to appear crack. The effect of casting procedure on crack formation is simulated by considering restraint degree and different shrinkage strain from the adjacent slab to each other.

Since the proposed structure is slab-on-grade, the boundary condition of subgrade is in accordance with the following; the bottom surface is restrained all directions (x, y, z direction) and the four-side surfaces are restrained in perpendicular direction. The slab area along with its thickness is restrained in all directions when it touches with wall or ground beam. Since the contraction joints are designed to deform freely in contraction or expansion, these joints' regions are taken as free.

4.5 Meshing

The meshing of slab is carried out in accordance with reinforcement spacing and the cover distance in actual slab. The subgrade meshing is also same with slab in contact direction but has wider meshing in thickness direction. After getting meshed, the steel reinforcement is created by connecting the nodes of the elements at same location. So there is no need to mesh the reinforcement. The mesh density is carried out by using two sizes, 100mm and 200mm in X and Z direction, but it cannot be change the size in Y direction in order to keep the same nodes with reinforcing streel bar layers. Figure 4-6 and Figure 4-7 shows meshing of model and geometry of meshing analysis. Figure 4-8, it is found that mesh size with 100 and 200 give similarity range of result but not same. Thus 100mm is chosen to mesh in the direction of X and Z direction.

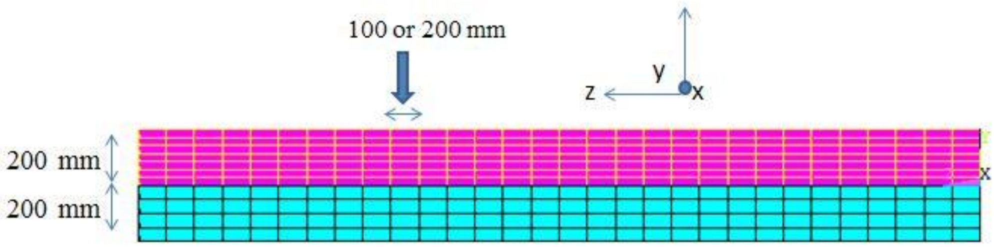

Figure 4.6: Meshing of the model in 100mm

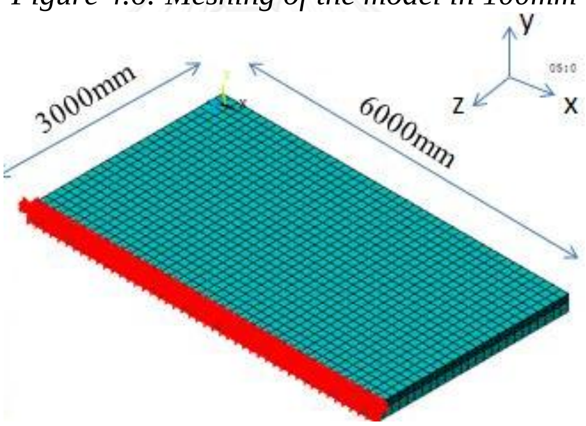

Figure 4.7: Geometry of meshing model

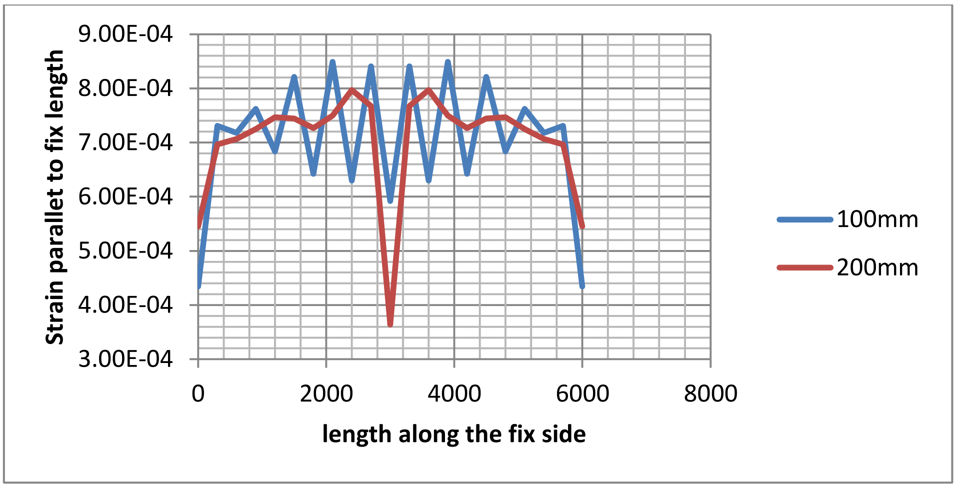

Figure 4.8: Comparison of Mesh size 100mm and 200mm in X and Z direction

4.6 Method

The static analysis will be performed in this research. For nonlinear analysis, the ANSYS program uses full Newton-Raphson procedure in which the model stiffness is updated at every equilibrium iteration[19].It divides the applied load to the model into load step which is a series of load increments[27] called substeps. According to the simulation of shrinkage, the input negative temperature will be divided into substeps and apply the model with increment series. The nonlinear analysis command in ANSYS program will be used in default. The convergence criteria will be on displacement because of the deformation after applying negative temperature.

4.7 Crack Width Perdition

The tensile strain and stress in concrete can simulate in the ANSYS program, but the crack width cannot get directly from the program. Therefore, to estimate the crack width has to rely on the equations from ACI code or Eurocode. It is calculated by tensile strain, strain based Eq 4.21 from reference [23] is used. This equation is also recommended in ACI Code.

$$w_c = \varepsilon_s S_c \quad \text{Eq 4.7}$$

$$S_c = \psi_s d^* \quad \text{Eq 4.8}$$

$$d^* = \sqrt{{d_c}^2 + \left(\frac{s}{2}\right)^2} \quad \text{Eq 4.9}$$

Where W_c= crack width

ε_s = reinforcing steel strain

S_c = crack spacing

Ψ_s = crack spacing factor (1.0 for minimum crack spacing, 1.5 for average crack spacing and 2.0 for maximum crack spacing)

d* = controlling cover distance

d_c = cover distance

s = spacing of steel bar

4.8 Verification of Finite Element Model in Projects

4.8.1 Finite Element Input Parameters

The finite element input parameters used for concrete, steel and subgrade model can be found in Table 4-1, Table 4-2 and Table 4-3 respectively. Most of the fundamental parameters received from the projects directly.

Table 4.1: FE Inputs of Concrete Model

Project	A	B
Item		
Element Type	Solid65	Solid65
Modulus of Elasticity, EX	Eq-4.5 (Mpa)	Eq-4.5 (Mpa)
Poisson Ratio, PRXY	0.2	0.2
Material Model in compression	multilinear curve	multilinear curve
Shear transfer coefficient for open	0.4	0.4
Shear transfer coefficient for close	1	1
Uniaxial tensile crushing stress	3.07	3.07
Uniaxial crushing stress	-1	-1
Density	2400 kg/m3	2400kg/m3
Coefficient of thermal expansion	10 x10-6 /$^{\circ}$C	10 x10-6 /$^{\circ}$C
Dimension of slab in Program	6x6x0.2 (m3)	9x5x0.2 (m3)

Table 4.2 : FE Inputs of Reinforcing Steel Model

Project	A	B
Item		
Element Type	Link180	Link180
Materail model	bilinear curve	bilinear curve
Real Constant	2x D12 @ 200mm	2x D12 @200mm
Modulus of Elasticity, EX	200,000 MPa	200,000 MPa
Poisson Ratio, PRXY	0.3	0.3
Yield strength	450MPa	450MPa
Density	7850 kg/m3	7850 kg/m3

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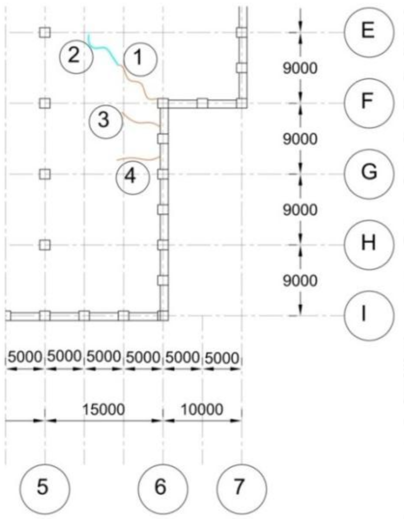
Table 4.3: FE Inputs of Subgrade Model

Project	A	B
Item		
Element Type	Solid65	Solid65
Material model	Dtrucker-Prager	Dtrucker-Prager
Modulus of Elasticity, EX	25MPa	25MPa
Poisson Ratio, PRXY	0.3	0.3
Density	2000kg/m3	2000kg/m3
Cohesion	0.02	0.02
Friction angle	35°	35°

4.8.2 Project A

The result comparison between the real projects and finite element analysis cannot coincide as experimental data. Thus, the crack width of collected data from the projects is compared with strain intensity in finite element program. In finite element implementation, the model is adopted from the cracked floor area cut by the contraction joints and the restrained boundary conditions, as fix. In project A, the crack lines start from the wall and columns called restraints. In Figure 4-9 shows the zoomed location of crack and crack width, and Figure 4-10 shows the dimensions of full slab in Project-A. However, in the finite element program, half of the slab is simulated.



Crack Point	Width (mm)	Length (mm)
1	0.4	1900
2	0.2	2300
3	0.15	1640
4	0.15	1750

Figure 4.9: Zoom of Location of Crack and Crack Width

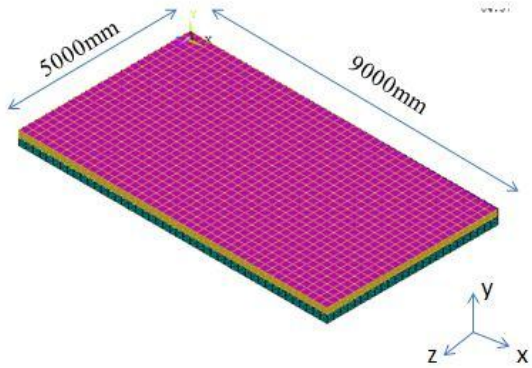


Figure 4.10: Geometry of Full slab in Project-A

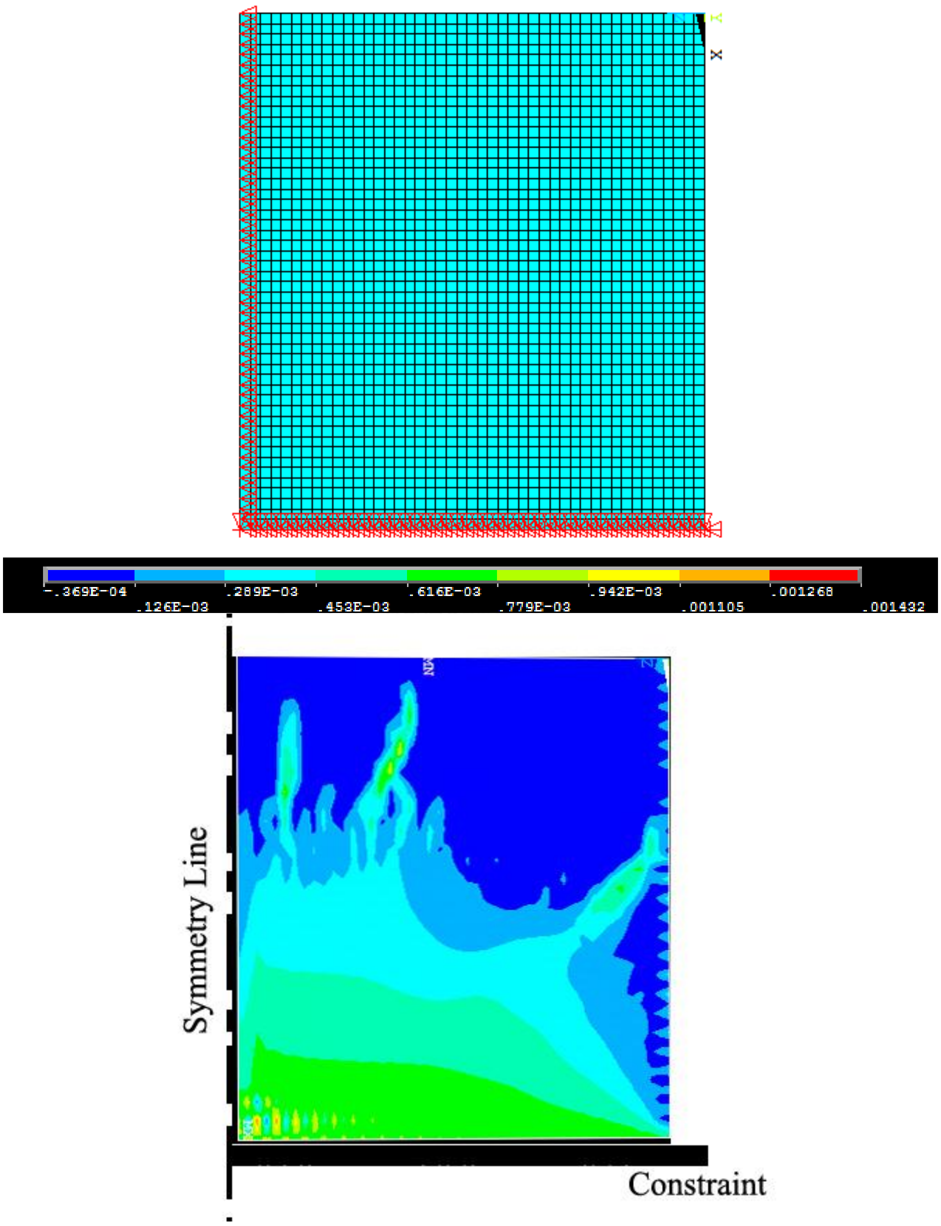


Figure 4.11: The contour plot strain intensity of slab model in longitudinal direction

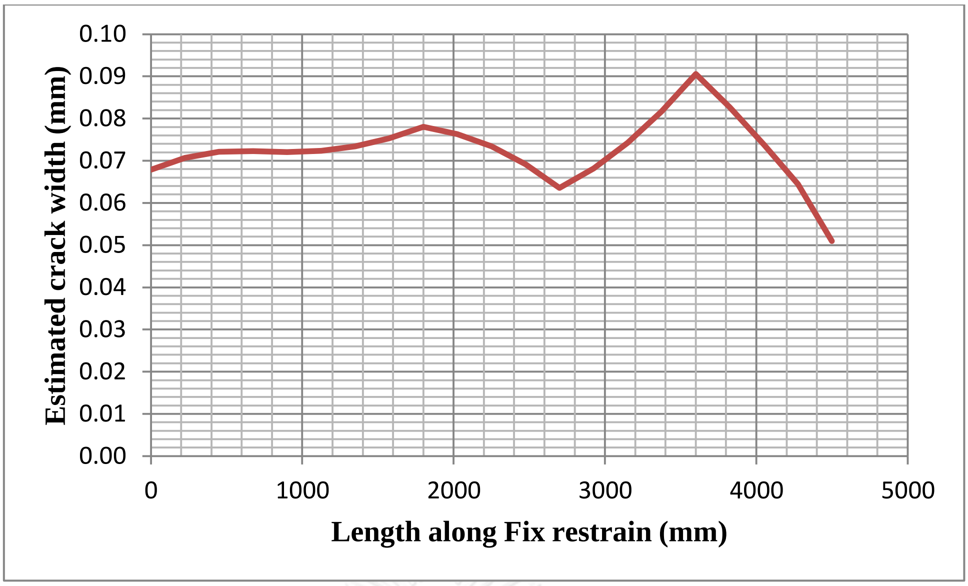


Figure 4.12: Estimated Crack Width along the Path of Fix Constraints

Figure 4-11 shows the strain intensity of contour plot in perpendicular direction to crack width. It can be seen that the strain becomes larger near the fix restraint, so it lets the influence of restraints on cracking distinct. In Figure 4-12, it shows the possible crack width along the fix side according to the crack width equation (Eq 4-7). Although the maximum crack width in Project-A is 0.4mm, it is 0.09mm from the program. From the figures, it can be seen that the maximum strain or crack width is generated near the center of the slab as in real project.

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4.8.3 Project B

In project B, the crack point-9 with 0.2mm width is simulated as there are many crack points. This crack point-9 is generated from the restrains called ground beam and wall. As mentioned in section 4.2, the slab in program is cut in line of contraction joints as shown in Figure 4-13 in red colored box. Figure 4-14 shows the geometry and boundary conditions of Project-B.

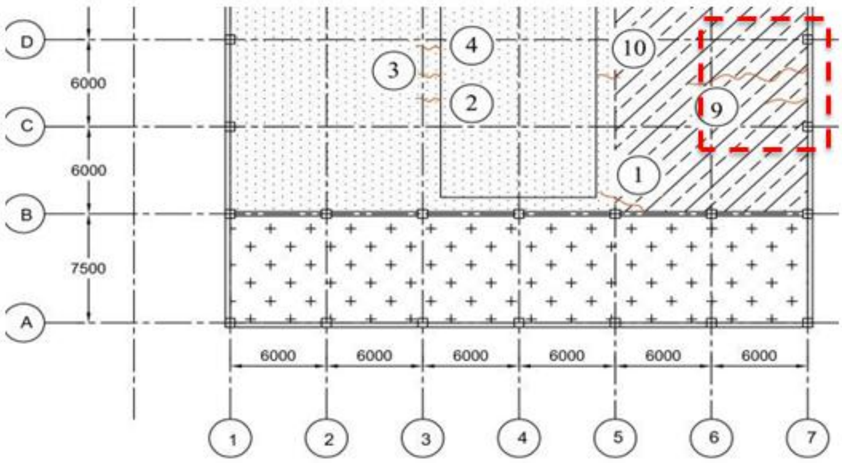

Figure 4.13: Zoom of Crack Point-9 Location in Floor Plan

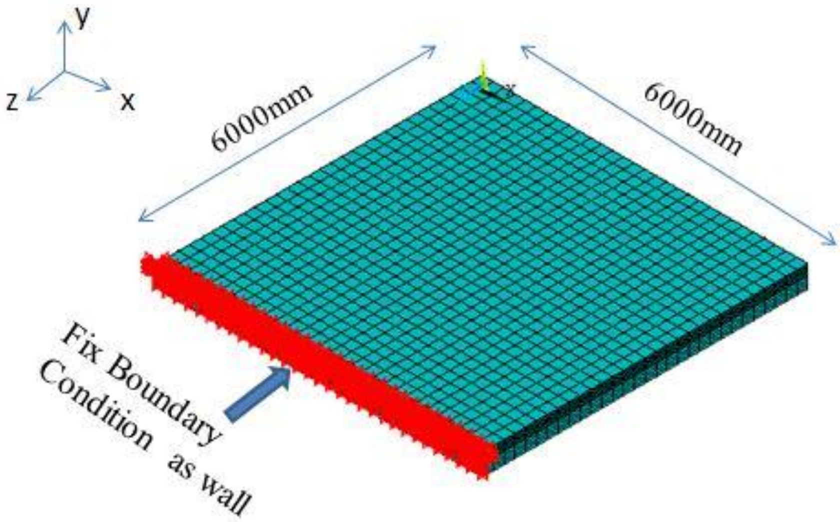

Figure 4.14: Geometry and Boundary Condition of Project-B

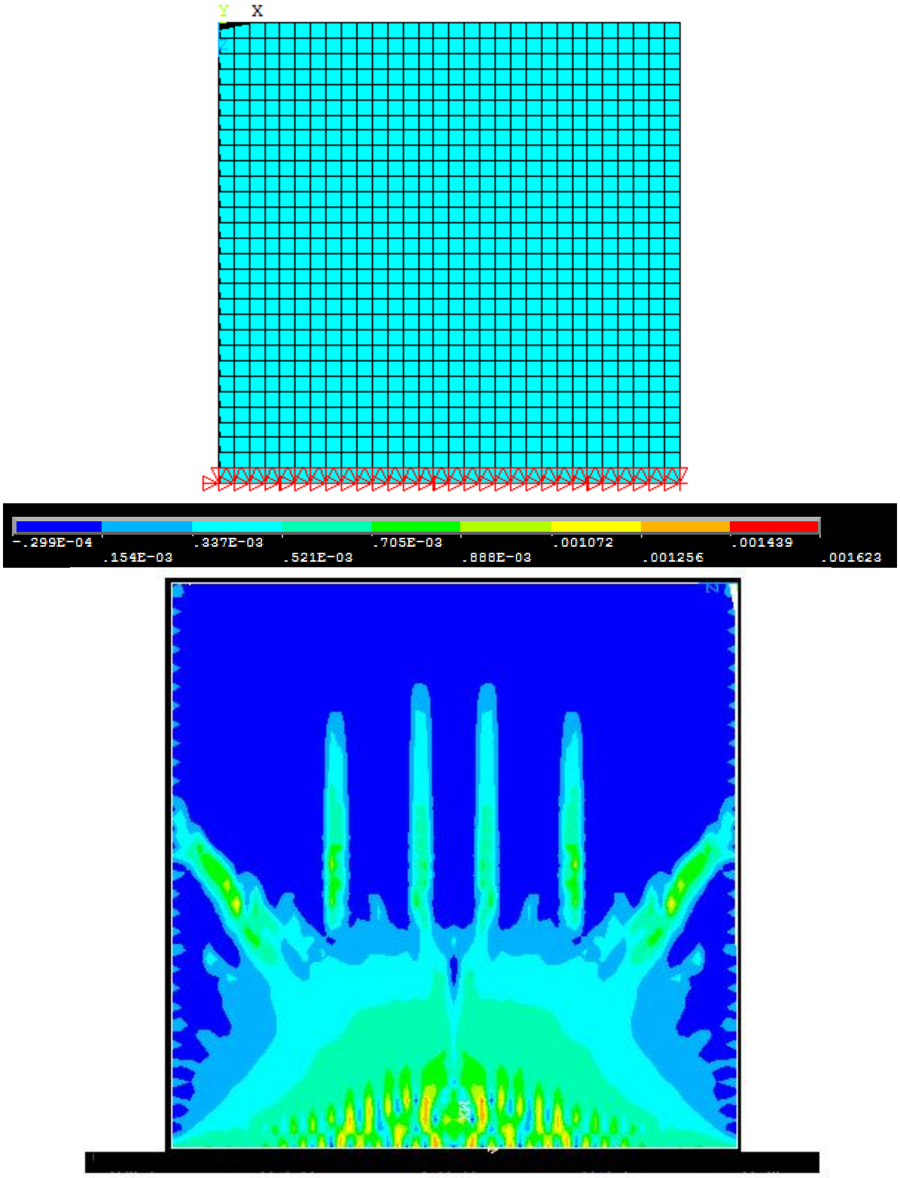

Figure 4.15: The Contour Plot Strain Intensity of Slab Model in Longitudinal Direction

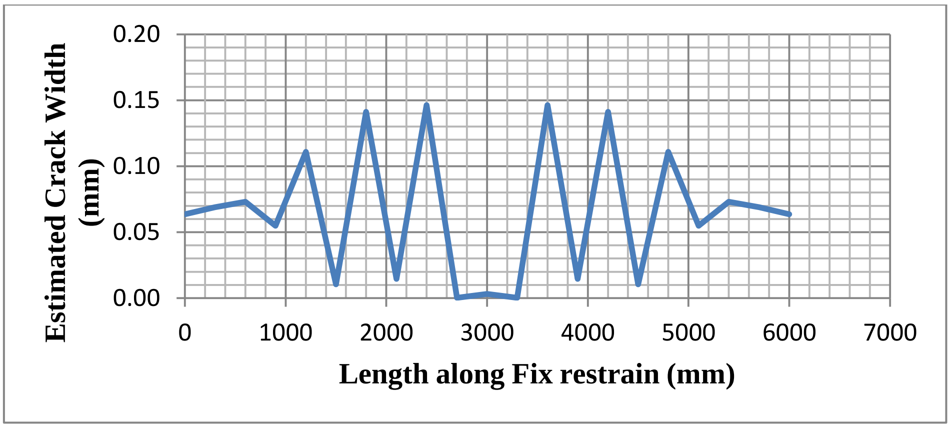

Figure 4.16: Estimated Crack Width along the Path of Fix Constraints

In Figure 4-15 shows the strain intensity along the fix length. Although the width of real crack and program crack is not matched definitely, the location of maximum strain intensity and crack width nearly matched those of real crack point-9 of the project. Thus it can be concluded that ANSYS can generate the crack in same location and nearly crack width.

4.9 Parametric Study

4.9.1 The Influence of Friction between slab and subgrade

The friction is one of the most restrained cases in slab-on-grade as it can disturb the freely contraction of concrete slab to some extent during shrinkage. In this thesis, the influence of friction on slab-on-grade is analyzed by coefficient of friction. The behavior between slab and subbase is modelled as contact element in ANSYS program as shown in previous section. In contact element, the friction coefficient is zero for frictionless and greater than zero for frictional case. That is why, using the coefficients of friction, 0, 0.75, 1 and 1.5, this section studies the influence of friction between slab and subgrade. Figure 4-17 shows the geometry and boundary condition of slab to analyze the influence of friction coefficient. In Figure 4-18, it can be seen generally that the increased friction coefficient let the crack width increase.

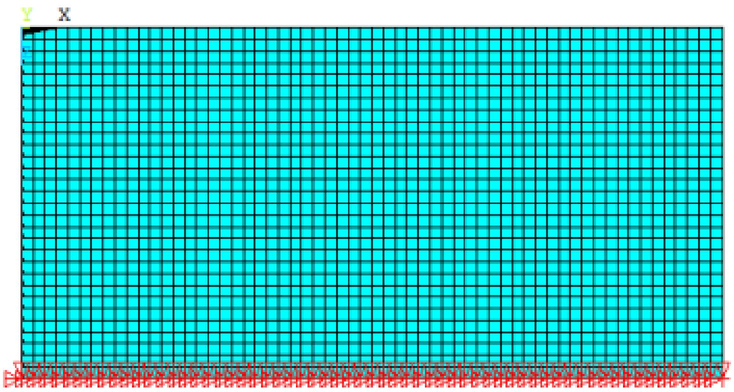

Figure 4.17: Geometry and Boundary Condition of slab used in analysis of friction coefficient

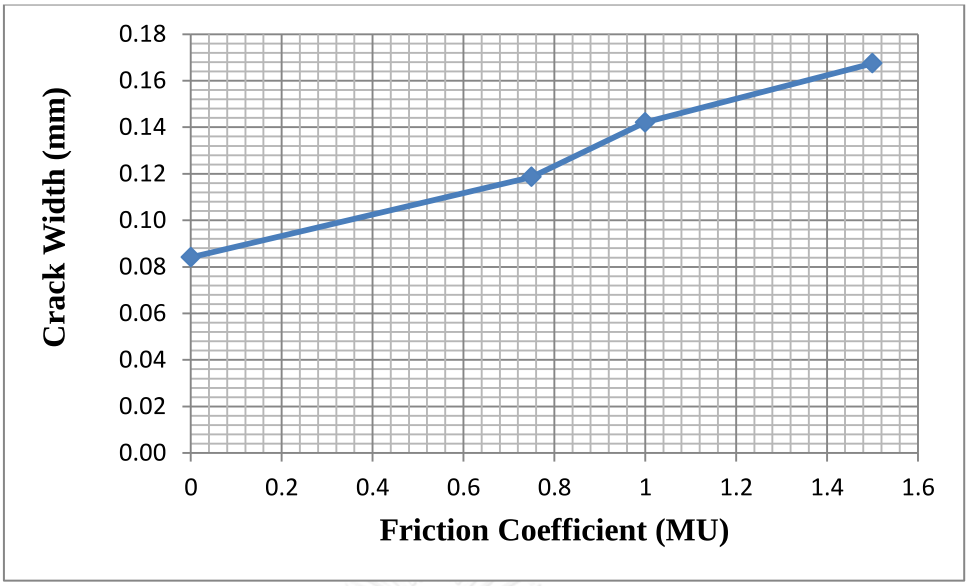

Figure 4.18: Crack Width versus Friction Coefficient

4.9.2 The impact of slab geometry

The geometry of slab in casting and joint cutting is apparently related to crack formation. The ratio of width to length of the slab should be kept in nearly square shape because the cracks can cause in perpendicular direction to the longer length or parallel to the shorter length. It can be seen by checking the strain intensity in Figure 4-20 and Figure 4-19 shows the geometry and boundary of slab. This parametric study shows how the length to width ratio affects the crack width. In this section, four slabs are carried out with same length and different width. That is why, there are four different ratio of width (W) to length (L); 1, 1.2, 1.5 and 2.

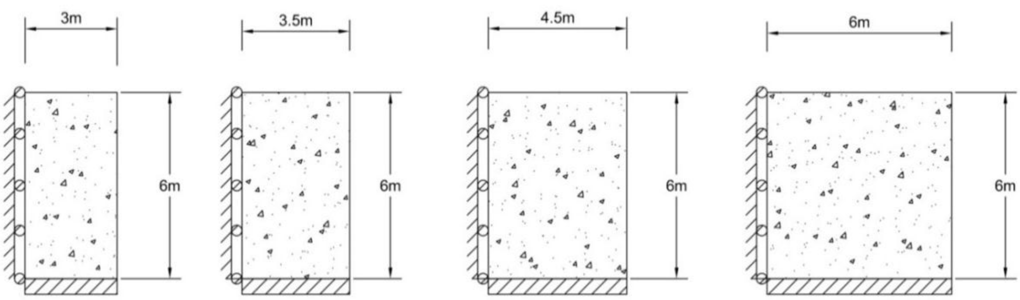

Figure 4.19: Different Geometries of slabs in half with same lengths and different widths

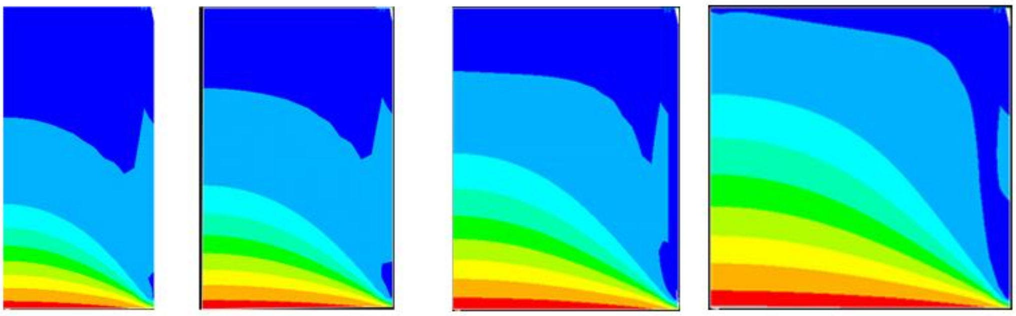

Figure 4.20: Comparison of Strain Intensity throughout Length of Four Slabs

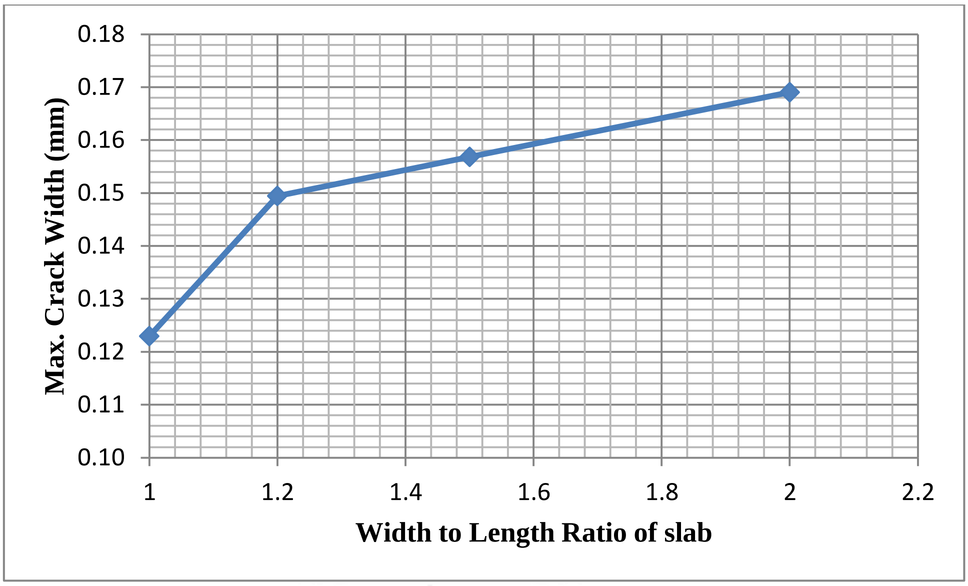

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Figure 4.21: Effect of Width to Length Ratio of Slab Geometry on Maximum Crack Width along the Fix direction

These four slabs in analysis are carried out using the same reinforcement arrangement of project-B.3D model of slabs are simulated with the advantages of symmetry and fully constrained along the width of slab. They are simulated under the same shrinkage stain at ε=0.00074 according to the project-B. The maximum concrete strain perpendicular to the crack width is considered to calculate the maximum crack width manipulated from the crack width equation Eq (4.7).

In the result section, the crack formation usually starts from the restrained edge to the opposite edge. The higher the ratio of width (restrained edge) to length of slab is, the more chance to bridge cracks from edge to edge. It can be seen in Figure 4-20 in which the distribution of strain intensity along the length of slab with different restrained widths. In Figure 4-21 shows that it also has the effect on crack width. In this figure, it shows the maximum crack width in constraint side(fix). Then, it can be found the directly proportion of restrained degree to crack width since the highest restrained degree of constrain side has largest crack width, and nearly no crack width is found along free end.

For these above reason, reducing W/L ratio of slab is one way in order to avoid the possible chance to have more cracking. Then it also gives more possible chance to have curling stress.

4.9.3 Casting Sequence

The restraint from casting sequence affects the formation of cracking largely as the observation of Project-B proves. In Project-A, most of the crack starts from the construction joints' cutting lines. Different casting sequences and times need different deformations of concrete, and the more strengthened adjacent member behaves as restraint to another one. According to the restrained degree, it can be known the probability of crack formation in slab. For these reasons, three kinds of casting sequence, A, B and C, is showed and discussed. The placing sequence A is continuous type, B is one line jump type and the last one, C is chart board type.

In the simulation, there are two types of slab; W/L=1 and W/L=1.8. This W/L ratio represents the width and length of slabs cut by contraction joints. Next, comparison is implemented according to the restraint degree equation as shown in Eq 4.24 mentioned in Chapter(2). In this equation, the imposed strain in case of full restraint, $-\varepsilon_{cT}$, is taken as one to be unity to simplify the FE calculation [30] and is also constant for all simulated slabs with different boundary conditions. Thus, the actual imposed strain is directly proportional to restraint degree. In this way, the restrain degree can be checked according to the strain intensity generated from program. The maximum strain in slab is represented in red color, and compressive strain in blue color under different restraint cases. Both two types of slabs have same range of contour color. Three types of casting sequence for two different slabs are carried out as followed. The mesh size used in this parameters study is 200mm in X and Y direction, in order to save time and only focus on the strain intensity.

$$R = \frac{\varepsilon_c}{-\varepsilon_{cT}} \qquad \text{Eq 4.10}$$

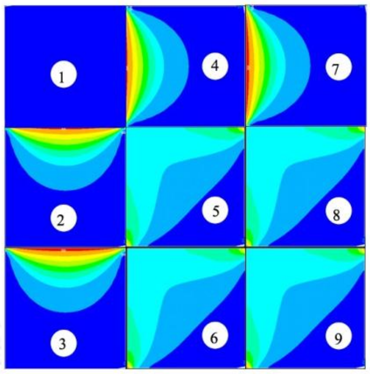

Figure 4.22: Casting Sequence A of Slabs with L/W=1

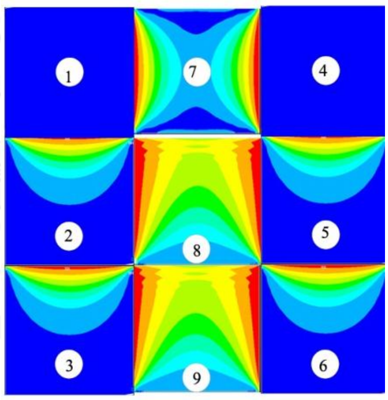

Figure 4.23: Casting Sequence B of Slab with L/W=1

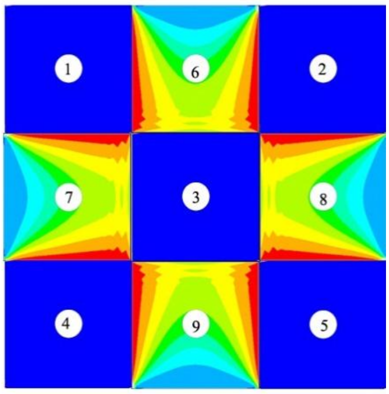

Figure 4.24 : Casting Sequence C of Slab with L/W=1

Figure 4-22 to Figure 4-24 shows three types of casting of L/W=1 slab. In the figures, the constrained sides are ranging from at least one to maximum three sides. When comparing restrained degree in different number of casting sides, it can be found the highest intensity in three-sided constrained.

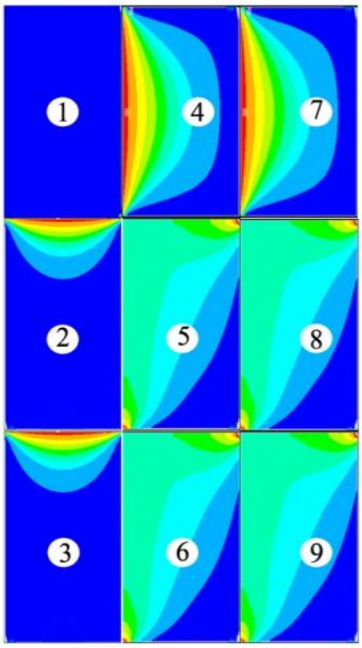

Figure 4.25: Casting Sequence A of Slab with L/W=1.8

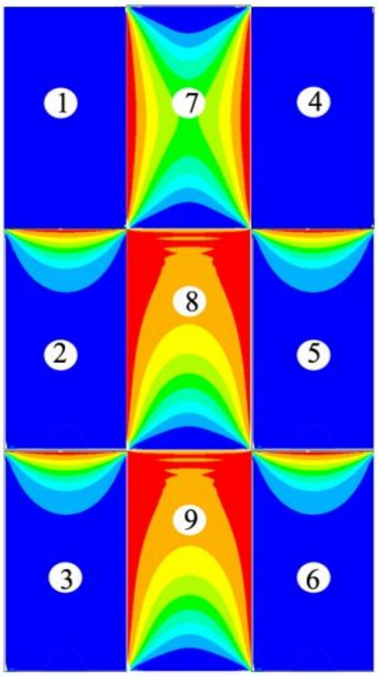

Figure 4.26: Casting Sequence B of Slab with L/W=1.8

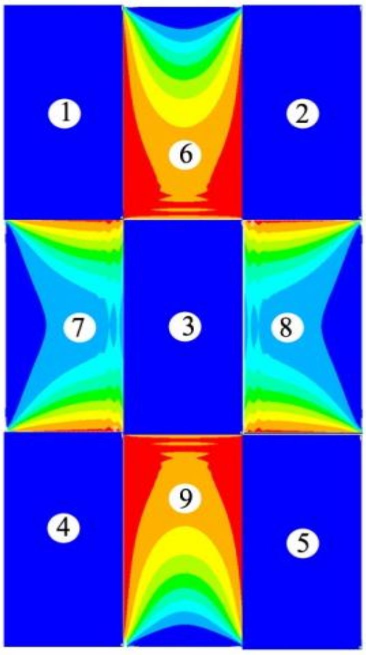

Figure 4.27: Casting Sequence C of Slab with L/W=1.8

From Figure 4.25 to Figure 4.27, they are three types of casting sequence with L/W=1.8. The potential of strain in short side and long side has large significant, so it should be constrained in shorter sides when it definitely needs to constraint. In this

L/W=1.8 slab, the maximum strength of restrained degree distribution is found in which two long sides and one side are restrained.

According to figures of the casting sequence of slabs, the more the touched area, the higher the restraint degree or stain intensity can cause. Therefore to decrease the restrain degree, it should be reduced the possible restraint cases which are controlling the number of constrained sides in L/W=1 and choosing the shorter sides to constraint in L/W<1.2. In the conclusion of casting sequence, the casting sequence A is least possibility of cracking formation since the strain intensity is less than the other kinds of casting and maximum touching parts is not more than two. Another advantage is that it is easy to cast when compared with others. For these reasons, casting sequence A is recommended to use.

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Chapter 5
Conclusion

In this thesis, with the purpose to minimize the shrinkage cracks in slab-on-grade, the study and observation of two real projects are carried out as a reference and the usual restraints, which are friction, W/L ratio and casting sequence, are simulated in ANSYS program.

In the section of reference project observation, the data measurement and collection was carried out after casting one year. The data includes crack width, crack length, crack location, floor plan and casting sequence of respective projects. It was found that most of the cracks come from restrained objects, such as ground beam, different casting slabs and walls. Then to measure the shrinkage strain directly from the projects is not easy, so the estimation or prediction was carried out, following the ACI Code.

In the finite element implementation, the comparison between the real project not under controlled and the finite element model is challenging task and can only be proved by the strain intensity generated from the restrained side. Then, from the real reference project, it can take the behavior and location of crack formation and material properties to simulate in the program. After that, it keeps on the parametric study. Firstly, the friction effect on crack width is carried out in which the higher friction coefficient can let wider crack in slab. Secondly, the study conveyed to influence of width (restrained side) to length of slab is investigated. In this case, the higher width to length ratio can have higher strain intensity and wider crack width. Thirdly, three types of casting sequence are carried out to investing their influence on restraint degree. There are two kinds of slab with L/W=1 and 1.8 in this section. In placing in square shape, the restrained degree is higher according to the number of constrained sides. For the slab with L/W=1.8, the lower restrain degree can be found when the shorter sides are constrained. Among three types of casting sequence for both types of slabs, type-A is found less restrained degree and recommended due to its easy access.

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For future recommendation, there are possible restraints left to investigate, such as reinforcement and aggregate as internal restraints since most of the investigation is focused on external restrained including this study.

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REFERENCES

1. *Guide for Concrete Floor and Slab Construction (ACI 302.1R-96)*. 1996, ACI Committee 302.
2. Narin, F. and O. Wiklund, *Design of Slabs-on-Ground Regarding Shrinkage Cracking*. 2012.
3. *Building Code Requirements for Structural Concrete (ACI 318M-11) An ACI Standard and Commentary*. 2011, ACI Committee 318.
4. *CIP-4 Cracking Concrete Surface* National Ready Mix Concrete Association (NRMCA)
5. Newman, J. and B.S. Choo, *Advanced Concrete Technology*. 2003, Amsterdam ; Boston: Elsevier Butterworth-Heinemann. v. <1- >.
6. Gromicko, N. and K. Shepard. *Visual Inspection of Concrete*. Available from: http://www.nachi.org/visual-inspection-concrete.htm.
7. Wight, J.K., et al., *Reinforced Concrete : Mechanics and Design (6th Edition)*. 6th ed. 2012, Upper Saddle River, N.J.: PEARSON PRENTICE HALL. xviii, 1157 p.
8. *Control of Cracking in Concrete Structure (ACI 224R-01)*. 2001, ACI Committee 224.
9. *CIP-42 Thermal Cracking of Concrete*. National Ready Mix Concrete Association (NRMCA)
10. *Effect of Restraint, Volume Change, and Reinforcement on Cracking of Mass Concrete.* ACI Materials Journal, 1990. **87**(3).
11. *"Design of Slabs-on-Ground (ACI 360R-06)"*. 2007, ACI Committee 360.
12. Parkes, N. *Designing the Cost-Effective Slab-On-Ground*. Apr,2007; Available from: http://www.structuremag.org/?p=6139.
13. Ytterberg, R.F., *Control of Shrinkage and Curling in Slabs on grade (Published in three parts)*. 1992.
14. Suprenant, B.A., *Vapor Barriers Under Concrete Slabs.*
15. Al-Gburi, M., J.-E. Jonasson, and M. Nilsson. *Effect of Casting Sequences on the Restraint In Slab-On-Ground*. in *Concrete Innovation Conference*. 2014.
16. Li, Z., *Advanced Concrete Technology*. 2011: John Wiley & Sons.
17. Antona, B. and R. Johansson, *Crack Control of Concrete Structures Subjected to Restraint Forces, Influence of Fibre Reinforcement*. 2011.
18. Johansson, M., *Structural Behavior in Concrete Frame Corners of Civil Defence Shelters*. 2000: Chalmers University of Technology.
19. *ANSYS 13.0.*
20. Kachlakev, D., et al., *Finite Element Modeling of Concrete Structures Strengthened with FRP Laminates.* Final report, SPR, 2001. **316**.
21. Nasvik, J. *Controlling Cracks in Slabs with Unusual Panel Geometries*. 2014; Available from: http://www.forconstructionpros.com/article/11264268/controlling-cracks-in-concrete-slabs-with-unusual-panel-geometries.
22. *Guide for Modeling and Calculating Shrinkage and Creep in Hardened Concrete*. 2008, ACI Comittee 209.R-08.

23. Kianoush, M., M. Acarcan, and A. Ziari, *Behavior of Base Restrained Reinforced Concrete Walls under Volumetric Change.* Engineering Structures, 2008. **30**(6): p. 1526-1534.
24. Kachlakev, D.I., *Finite Element Analysis And Model Validation of Shear Deficient Reinforced Concrete Beams Strengthened with GFRP Laminates.*
25. Attiyah, A.N., H. Gesund, and M.H. Rasool, *Finite Element Modelling of Concrete Shrinkage Cracking in Walls.* Kufa journal of Engineering, 2014. **5**(1).
26. Al-Azzawi, A., A. Mahdy, and O.S. Farhan, *Finite Element Analysis of Deep Beams on Nonlinear Elastic Foundations.* Journal of the Serbian Society for Computational Mechanics/Vol, 2010. **4**(2): p. 13-42.
27. Perera, U., *Seismic Performance of Concrete beam-slab-Column Systems Constructed with a Re-usable Sheet Metal Formwork System.* 2007.
28. Vacev, T., et al., *Testing and Finite Element Analysis of Reinforced Concrete Column Footings Failing by Punching Shear*. Engineering Structures, 2015. **92**: p. 1-14.
29. *Geotechdata.info, Angle of Friction, http://geotechdata.info/parameter/angle-of-friction.html*. 14.12.2013; Available from: http://www.geotechdata.info/parameter/angle-of-friction.html.
30. Al-Gburi, M.A., J.-E. Jonasson, and M. Nilsson, *Using Artificial Neural Networks to Predict the Restraint in Concrete Culverts at Early Age.* Structural Engineering International, 2015. **25**(3): p. 258-265.

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APPENDIX

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Appendix- 1: How to calculate Shrinkage Strain in Project-A

Problem Data								
Concrete Data								
Compressive strength of conc.	f'c	21	Mpa					
Unit weight of conc.	Rc	2345	kg/m3					
Slump	S	125	mm					
Fine aggregate percentage	Ψ	40	%					
Cement Content	C	300	kg/m3					
Water content	W	171	kg/m4					
Water-cement ratio	w/c	0.57						
Air content factor	A	1	%					
Ambient condition								
Relative humidity	H	0.4	decimal					
Ambient temperature	T	30	C					
Specimen				L	W	Thk		
Volume surface ratio	V/S	100	mm	6000	6000	200		
Initial Curing								
Water curing period	Tc	7	days					
ACI 209R Model Solution								
1. Estimated conc. properties								
Mean 28 days Strength	fcm28	29.3	Mpa					
Mean 28 days elastic modulus	Ecm28	26431.18	Mpa					
2.Shrinkage Strain								
Normal Ultimate shrinkage strain	ε(shu)	7.80E-04						
Moist curing correction factor	r(sh,tc)	1.005092						
Ambient relative humidity factor	r(sh,RH)	0.992						
Volume to surface rotio factor	r(sh,vs)	0.748504						
slump of fresh concrete factor	r(sh,s)	1.09125						
Fine aggregate factor	r(sh,Ψ)	0.86						
Cement Content Factor	r(sh,c)	0.933						
Air content Factor	r(sh,α)	1.0						
Cumulative correction factor	r(rh)	0.653456						
Ultimate Shrinkage Strain	ε(shu)	5.10E-04						
Drying period	t	7.00	14	28	60	90	180	365
	α	1	1	1	1	1	1	1
Shrinkage Time function	f(t,tc)	0.00	0.167	0.375	0.602	0.703	0.832	0.911
Shrinkage Strains	ε(sh)(t,tc)	0.00E+0	8.49E-5	1.91E-4	3.07E-4	3.59E-4	4.24E-4	4.64E-4

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Appendix- 2: How to calculate Shrinkage Strain in Project-B

Problem Data								
Concrete Data								
Compressive strength of concrete	f'c	21	Mpa					
Unit weight of conc	rc	2345	kg/m3	standard				
Slump	s	100	mm					
Fine aggregate percentage	Ψ	40	%					
Cement Content	c	285	kg/m3					
Water content	w	163	kg/m3					
Water-cement ratio	w/c	0.572						
Air content factor	α	1	%					
Ambient condition								
Relative humidity	Rh	0.4						
Ambient temperature	T	30	C(Thai temp)					
Specimen				L	W	Thk		
Volume surface ratio	V/s	100	mm	6000	6000	200		
Initail Curing								
Water curing period	tc	7	days					
Curing condition	mositure	moist cured						
ACI 209R Model Solution ***1. Estimated concrete properties***								
Mean 28 days Strength	fcm28	29.3	Mpa					
Mean 28 days elastic modulus	Ecm28	26431.18	Mpa					
2.Shrinkage Strain Normal Ultimate shrinkage strain	ε(shu)	7.80E-04						
Moist curing correction factor	r(sh,tc)	1.005092						
Ambient relative humidity factor	r(sh,RH)	0.992						
Volume to surface rotio factor	r(sh,vs)	0.748504						
slump of fresh concrete factor	r(sh,s)	1.051						
Fine aggregate factor	r(sh,Ψ)	0.86						
Cement Content Factor	r(sh,c)	0.92385						
Air content Factor	r(sh,α)	1.0						
Cumulative correction factor	r(rh)	0.623181						
Ultimate Shrinkage Strain	ε(shu)	4.86E-04						
Drying period	t(day)	7	14	28	60	90	180	365
	α	1	1	1	1	1	1	1
Shrinkage Time function	f(t,tc)	0.00	0.167	0.375	0.602	0.703	0.832	0.911
Shrinkage Strains	ε(sh)(t,tc)	0.00E+0	8.10E-5	1.82E-4	2.93E-4	3.42E-4	4.04E-4	4.43E-04

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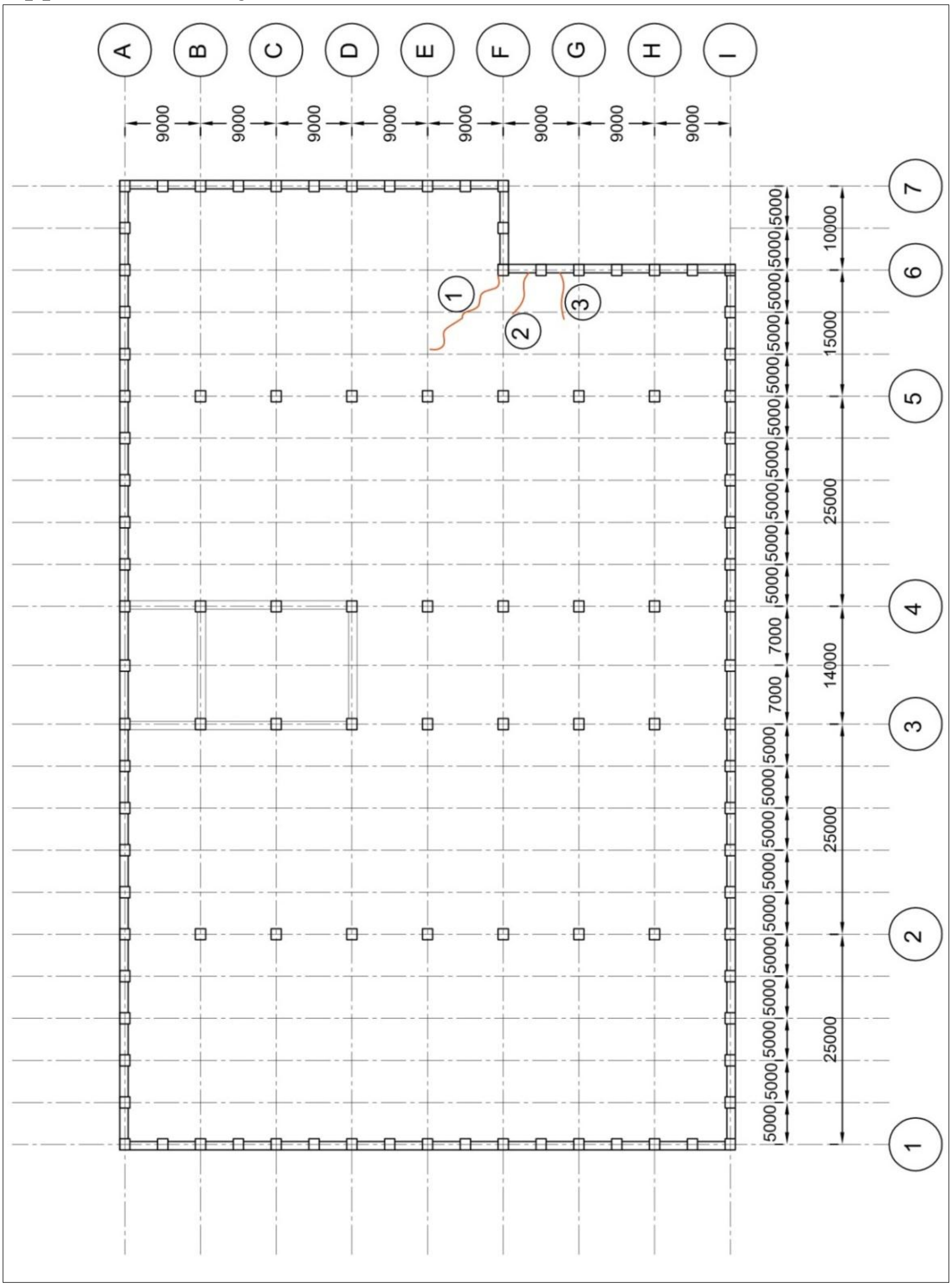
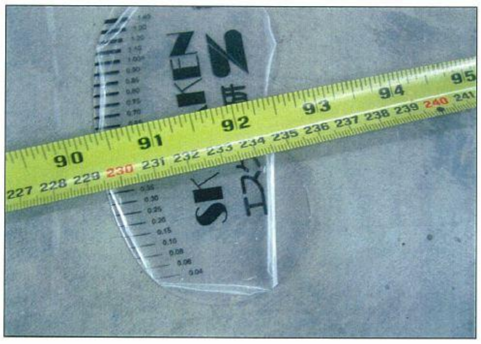
Appendix- 3: Project- A Data Collection



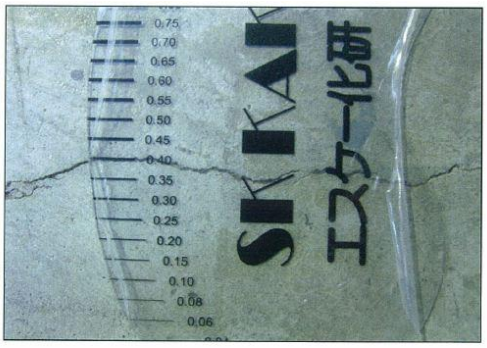
Floor Plan of Project-A and Location of crack lines

Location of floor crack at column line G/6 . (point 1)



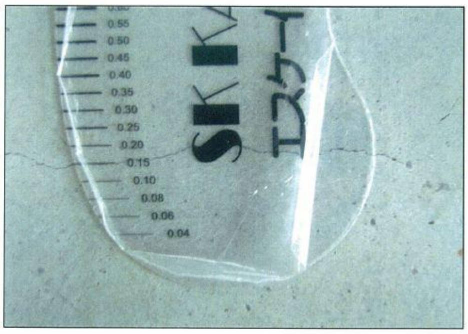
Floor crack long 2,300 mm. , 0.20mm .

Floor crack at column line G/6 . (point 1)



Floor crack 0.40mm long 1,900mm.

Floor crack at guard pole line G/6 . (point 2)



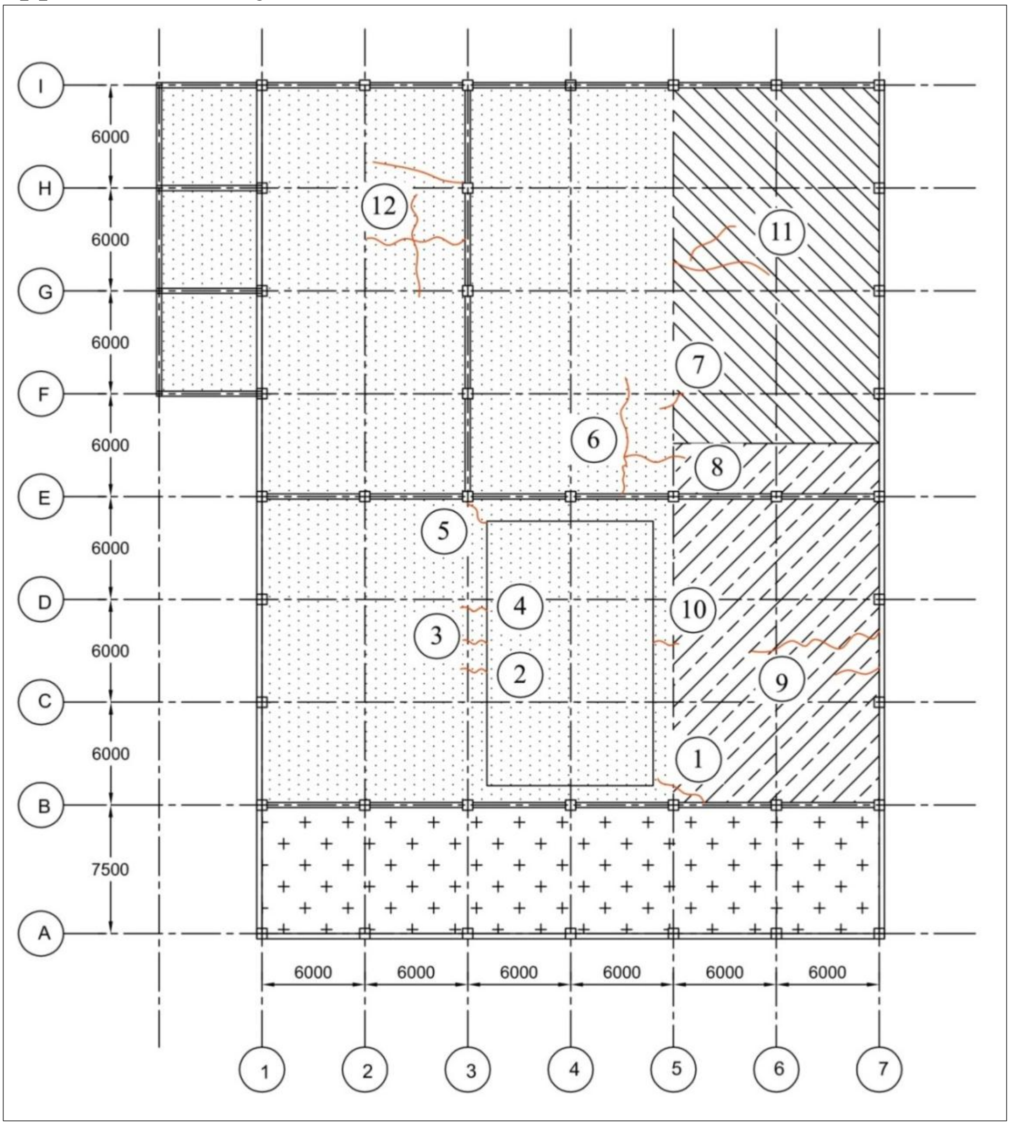
Floor crack 0.15mm long 1,640mm.

Floor crack at guard pole line G/6 . (point 3)

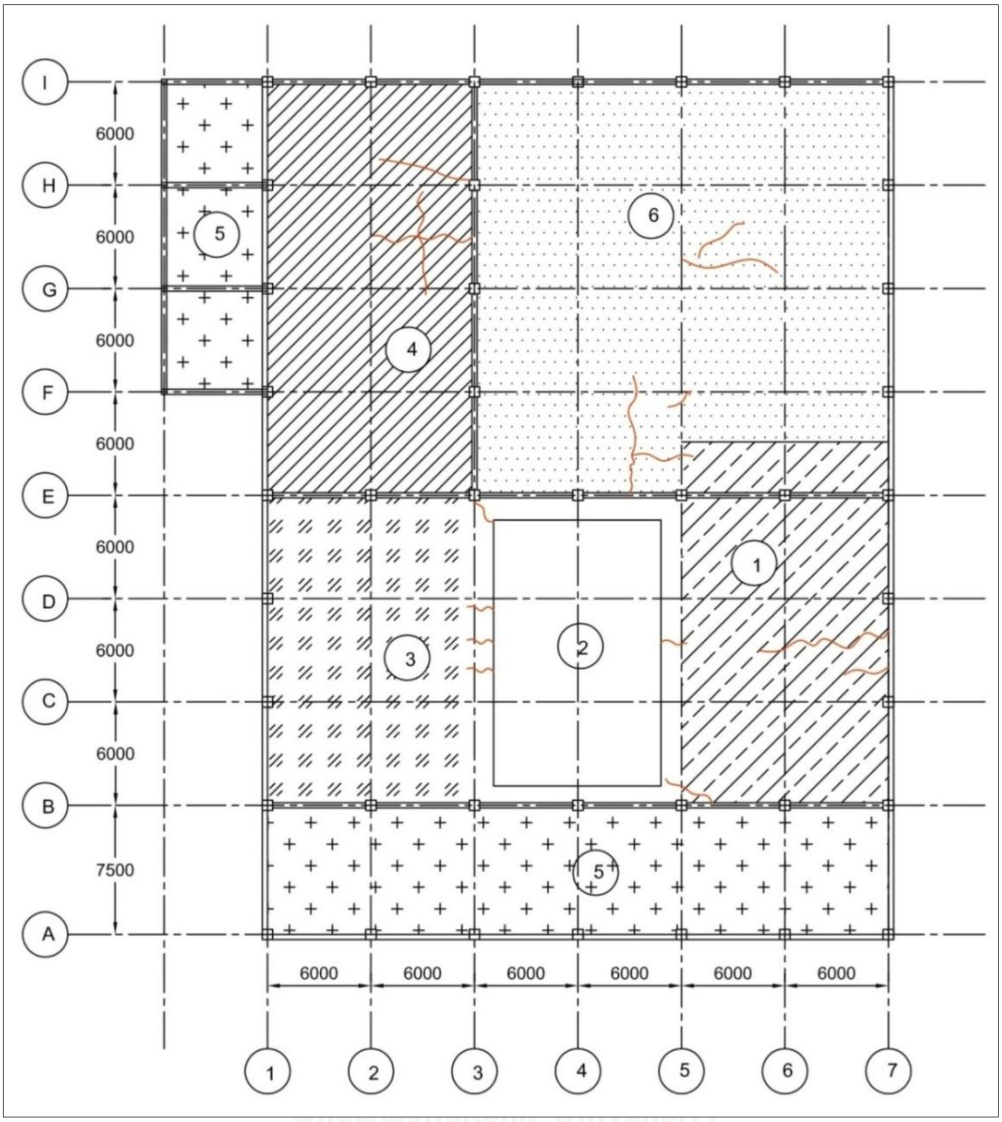
Floor crack 0.15mm long 1,750mm.

Measurement Carried Out in Project-A

Appendix- 4: Project- B Data Collection

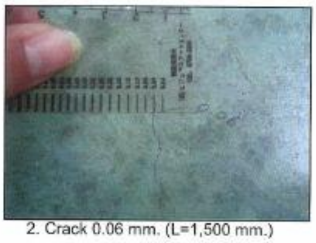


Crack Location in Floor Plan of Project-B



Casting Sequence of Project-B

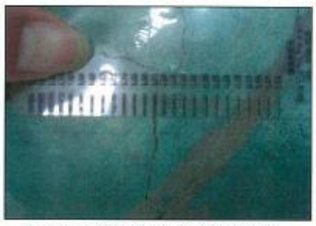
1. Crack 0.08 mm. (L=2,000 mm.)



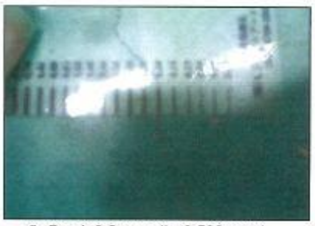
2. Crack 0.06 mm. (L=1,500 mm.)

3. Crack 0.08 mm. (L=1,500 mm.)

4. Crack 0.06 mm. (L=1,500 mm.)



5. Crack 0.55 mm. (L=1,800 mm.)



6. Crack 0.2 mm. (L=6,500 mm.)

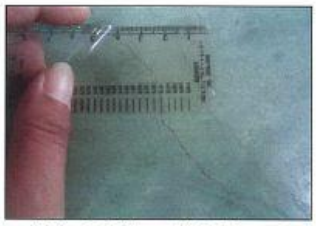
7. Crack 0.2 mm. (L=4,000 mm.)

8. Crack 0.15 mm. (L=4,000 mm.)

9. Crack 0.2 mm. (L=8,500 mm.)

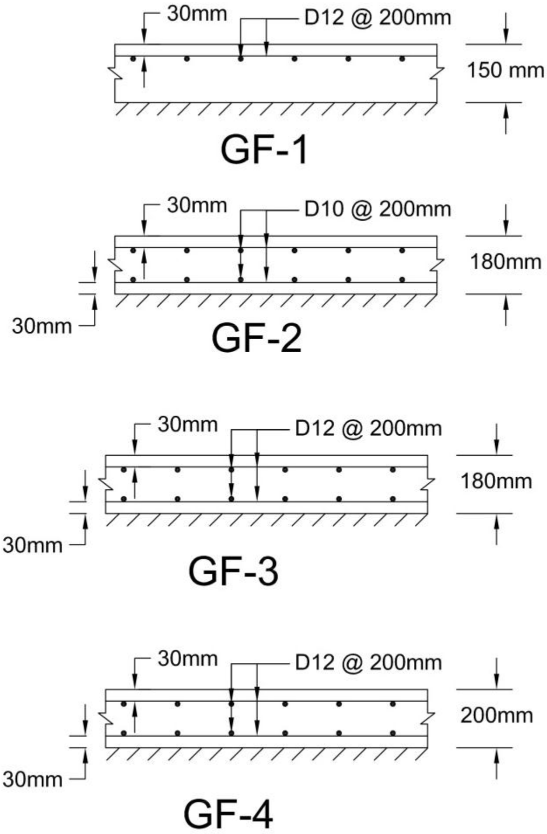
10. Crack 0.15 (L=1,500 mm.)

11. Crack 0.04 mm. (L=9,000 mm.)

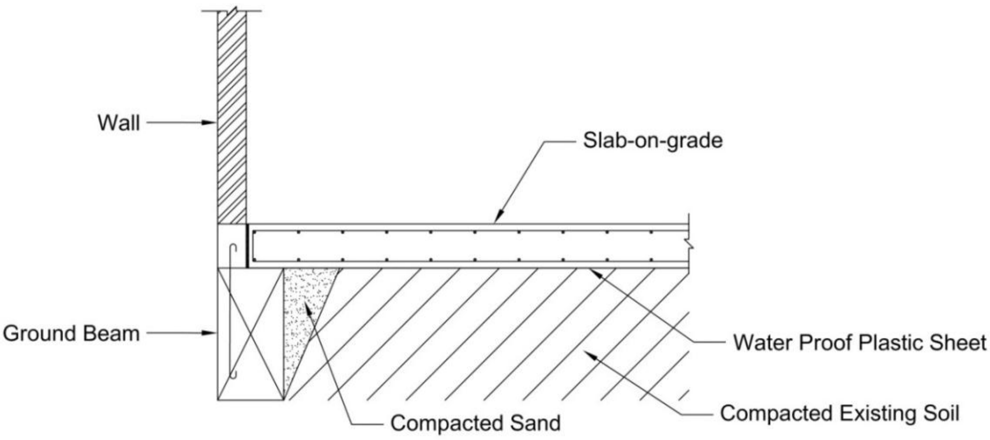


12. Crack 0.15 mm. (L=8,000 mm.)

Measurement carried out in Project-B



Slab designs used in Project-B



Cross-Section of Slab at the Edge or Near Ground Beam

VITA

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