

ADDIS ABABA UNIVERSITY
ADDIS ABABA INSTITUTE OF TECHNOLOGY
SCHOOL OF CIVIL AND ENVIRONMENTAL
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Experimental Investigation on Interface Shear and Tensile
Strength Between Old and New Concrete at Different Moisture
Condition

A Thesis in Structural Engineering

By Jemal Kedir Adem

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A Thesis

Submitted in Partial Fulfillment of the Requirements for the Degree of Master of Science

The undersigned have examined the thesis entitled “**Experimental Investigation on Interface Shear and Tensile Strength Between Old and New Concrete at Different Moisture Condition.**” Presented by **Jemal Kedir Adem**, a candidate for the Degree of Master of Science in structural engineering and hereby certify that is worthy of Acceptance.

Approved by the Board of Examiners:

Dr. Esayas Gebreyouhannes

Advisor

Signature

Date

Dr. Ing. Adil Zekeria

Internal Examiner

Signature

Date

Dr. Ing. Girma Zerayohannes

External Examiner

Signature

Date

Dr.-Ing. Mebruk Mohammed

School Dean

Signature

Date

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.....
Jemal Kedir Adem

ABSTRACT

This research work is dedicated to experimental investigation on interface shear and tensile strength between old and new concrete. Twenty Push-off specimens were cast on the experimental program of the shear test. Nine specimens were monolithically cast and eleven specimens were cast with an interface. The surface of the substrate concrete was left as cast. The shear specimen was tested by varying confinements i.e. without confinement bar, with $100\mu\epsilon$ and $125\mu\epsilon$ initial confining strains. In addition to the above parameters, environmental conditions i.e. dry and wet conditions were also considered in this research.

It was observed from this experimental program that the presence of an interface between old and new concrete causes a reduction of shear and tensile strength. For shear specimens, a reduction in shear strength of 77.39 %, 54.07 % and 38.92% for without confinement, $100\mu\epsilon$ initial confinement strain, and $125\mu\epsilon$ initial confinements respectively were obtained. The presence of water also has an adverse effect on the shear strength of concrete a reduction of up to 10% was observed.

Nine specimens were cast on the experimental program for the tensile test. Three specimens with interface and dog bone shaped mold were cast and tested using direct tensile test six cylindrical specimens were cast monolithically. This experimental program also indicated the presence of an interface between old and new concrete reduces tensile strength by 50%-70%.

The roughness of the shear specimen was measured. For monolithically cast surface arithmetic mean deviation of the profile, R_a coefficient, was higher and for cast with interface sample, R_a was smaller. The roughness was measured for five specimens. Evidently, as mean roughness increases shear bond strength also increase.

A model of the specimen for both shear and tension without an interface was simulated on a nonlinear finite element analysis program DuCOM-COM3 for monotonic loading. The ultimate load was captured in fair proximity with the model.

Keywords: Push-off, Shear capacity, Dog-bone, Tensile capacity, Environment condition, Interface, Bond, Confinement strain, Mapping of surface profile.

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LIST OF ABBREVIATIONS

ISD	Cast with Interface specimen shear strength at dry environmental condition
ISW	Cast with Interface specimen shear strength at wet environmental condition
ITD	Cast with Interface specimen tensile strength at dry environmental condition
MSD	Monolithically cast specimen shear strength at dry environmental condition
MSW	Monolithically cast specimen shear strength at wet environmental condition
MTD	Monolithically cast shear strength at dry environmental condition
NCS	No confinement strain (without confinement bar)
R _a	Arithmetic mean deviation of roughness profile
μ ϵ	Microstrain

CHAPTER 1 INTRODUCTION

1.1 General Background of the Study

The Interface strength between old and new concrete is a very important parameter in concrete repair. The repair material contains three parts substrates, overlay, and Interface zone. The Interface zone is the interface between old and new concrete. The interface between old and new concrete must be capable of withstanding the stresses imposed on the system. In the interface zone, the failure mode is either in shear or tension. The Interface strength at the interface between concrete layers cast at different times is important to ensure monolithic behavior for serviceability limit state and safety for ultimate limit state.

In construction, there is a delay in construction as well as the need for maintenance of concrete and needs for strengthen of concrete structure. Bonded concrete overlay is a viable option to increase the structural capacity of concrete bridges and pavements and buildings. With property mismatch of new overlaid concrete to old concrete, however, bonded concrete overlays may lead to early age failure and a shortened service life. To better understand the bonding mechanism at the interface between new and old concrete surfaces, it is essential to measure interface strength at the interface and to investigate affecting parameters of its properties.

1.2 Statement of the Problem

Due to following reasons the need to overlay concrete over the substrate surface concrete with creating an Interface zone or interface between old and new concrete.

1. Structural Strengthen of concrete

Structural strengthening is the process of upgrading structures to improve performance under existing loads or to increase the strength of structural members to carry additional loads.

2. Maintenance of Concrete Structure

Maintenance of concrete is needed due to deterioration of concrete structures which start usually at the surface of the concrete members and damages because of wars, earthquake and other accidents.

3. Casting Delay of Concrete in Construction

Casting delay of concrete is one of the common problems encountered in concrete industry. The delay in placing of concrete may arise due to any factors like glitch in casting machinery, improper site conditions, unskilled handling practices etc. which result in loss of material and money. Casting delay begins from one day but may take even months. Previous research was done by (Zerabruk, 2015), (Solomon, 2018) and (Tadesse, Seifu, Gebeyehu, Ababu, & Tesfaye, 2018) for construction joint casted 24 hours apart.

4. Extension of Building

An extension is a new room or building which is added to an existing building or group of buildings and it needs proper match of the old structure and new structure.

5. Change of Function

A change of function or design change is the modification conducted to the product. It can happen at any stage in the product development process or after construction was done can also made change of function of the structure.

Due to these reasons the need to overlay concrete over the substrate surface concrete with creating a Interface zone or interface between old and new concrete, To enhance the quality of maintenance of infrastructure by overlaying with maintenance or strengthening materials, it is essential to understand the mechanical properties and behavior at the interface and the reduction on shear and tension between old construction material and new strengthening or maintenance material since the interface is the weakest link.

1.3 Objective of the Study

1.3.1 General Objective

The thesis aims to experimentally investigate on interfacial shear strength and tensile strength of old and new concrete at different moisture conditions.

1.3.2 Specific Objective

- To study shear behavior of concrete with an interface using push-off shear test.
- To quantify a confinement effect on interface shear strength.
- To study the tensile behavior of concrete with an interface using a direct tensile test under dry air condition.
- To study roughness and shear strength relation between the monolithically cast specimen and cast with interface specimen.

1.4 Scope and limitations of the study

Scope of the study

The experimental investigation is focused on interface behavior of concrete where the substrata is 28 days age. Two loading conditions, namely shear and tension are considered both under day and water submerged condition.

Limitation of the study

The adverse effect of additional long-term deformations was neglected in this study. Keeps another parameter other than specifies in scope that affects Interface strength was constant.

1.5 Methodology

The methodology used in this study is experimental supported with literature data analysis. And finite element analysis was done for verification. Comprehensive literature review related to investigating Interface strength between old and new concrete was conducted.

Systematic experimental program was designed to address the shear behavior of old new concrete using push off test. Experimental program was also designed to address the tensile behavior of old new concrete using direct tensile test. Roughness of the specimen was mapped using a handmade profilometry. Finally, analytical simulation using non-linear finite element software incorporating outputs of the experimental program was done.

1.6 Organization of the Thesis

This thesis consists of five chapters arranged carefully in order to make it clear and understandable. This section presents a brief description of these chapters.

Chapter (1): In this chapter, the statement of the problem, objectives of the research and scope and limitation in the research are included.

Chapter (2): Provides a comprehensive review of relevant previous research related to the rehabilitation methods and surface roughness evaluation.

Chapter (3): Outlines the standards, procedures adopted, material properties and testing program, test set up and instrumentation.

Chapter (4): Explaining the result and discussion of the findings.

Chapter (5): Provide finite element modeling.

Chapter (6): Includes the general conclusion from this research work are presented in addition to recommendations for future research.

CHAPTER 2 LITERATURE REVIEW

2.1 General Background

The three forces most applied on concrete are compression, shear and tension and since concrete are strong in compression and weak in shear and tension this research focuses on shear and tensile reduction of concrete because of the interface.

There are many reasons for crating interface between old and new concrete. structural strengthen of concrete, maintenance of structure, casting delay of concrete, extension of new structure, and change of function of the building.

Strengthening of concrete structures must be considered when the existing structure deteriorates or any alteration to the structure has to be made due to which the structure may fail to serve its purpose.

Maintenance of concrete structures is needed due to many reasons, such as the deterioration of the concrete structures which start usually from the surface of the concrete members, the need to change the purpose of buildings occupation, and exposing damages because of wars. The most common rehabilitation technique evolves enlarging structural members by adding a new topping concrete layer for the slabs, and column jacketing in case of damaged columns. This technique of rehabilitation, to be efficient, the old section should interact with the new section monolithically. This will lead to monolithic failure at the ultimate load. Otherwise, each member fails individually. Thus, the rehabilitation will not be efficient (F.AIHallaq Ahmed, 2014).

Due to these reasons the need to overlay concrete over the substrate surface concrete with creating a bond zone or interface between old and new concrete. which is called rehabilitation of Concrete structure. To enhance the quality of maintenance of infrastructure by overlaying with new maintenance materials, it is essential to understand the mechanical properties and behavior at the interface and the degradation on shear and tension between old construction material and new maintenance material since the interface is the weakest link(Espeche & León, 2011) and (Wan & Shin, 2010) .

2.1.1 Interface Strength Evaluation

The existing test methods to determine the interface strength between new and old concrete can be categorized in to three groups:(1) tension; (2) shear and compression;(3) direct shear method. Generally, Espeche and León (Espeche & León, 2011) presented a schematic representation of various interface shear and tensile strength Figure 2-1.

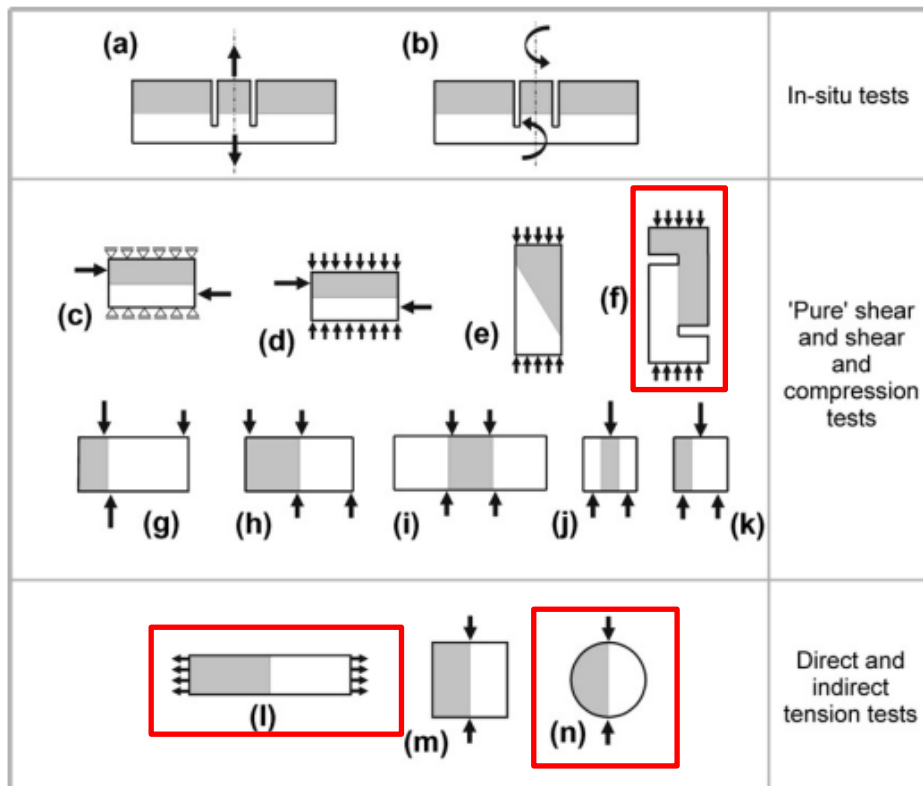


Figure 2-1: Schematic representation of different shear and tensile bond strength tests (Espeche & León, 2011).

Direct shear test (Push off-test) is the most popular test method utilized in laboratory. Indirect tension tests include the flexural test and the splitting tensile test. The flexural test offers low efficiency. at performing a good tension test is difficult and time consuming and dog bone mold uses for direct tensile strength test.

2.2 Shear Transfer Mechanisms

Shear is transferred using three mechanisms adhesive bond, friction and dowel action. As stated in Figure 2-2 , the shear strength at a concrete-to concrete interface can be described by a combination of three different load-carrying mechanisms:

- a) Adhesion
- b) shear-friction
- c) shear reinforcement

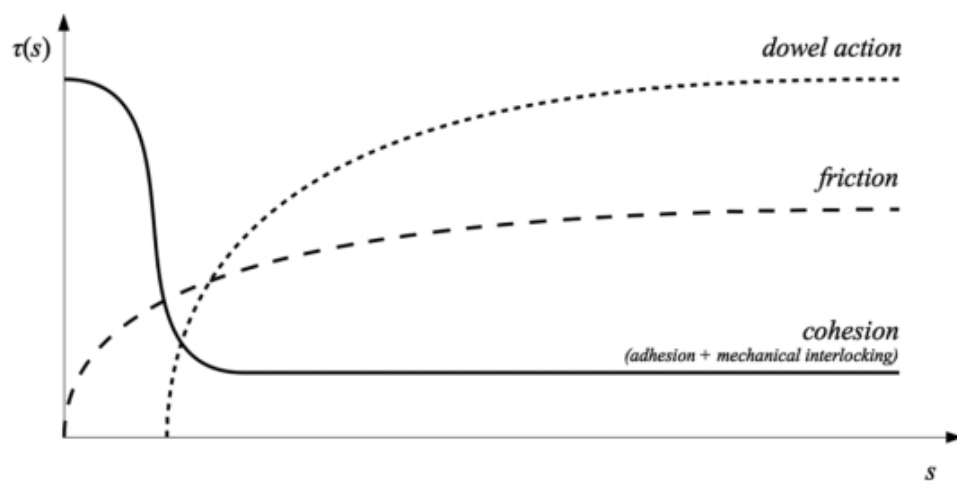


Figure 2-2: Contribution of adhesion, shear-friction and shear reinforcement(Pedro M.D. Santos & Júlio, 2014).

The adhesion component is originated by chemical bond connections between the particles of old and new concrete. When its maximum load capacity is reached, debonding occurs at the concrete-to-concrete interface and the shear stresses will be transferred by mechanical (Aggregate) interlocking. If the interface is subjected to compression, the shear stresses will be transferred by shear-friction. With the increase of the relative displacement between concrete parts, the reinforcement that crosses the interface will be tensioned and yielding can occur. Therefore, the shear reinforcement will induce compression at the interface and the shear load will be transferred by friction. Due to slippage, the shear reinforcement will also be subjected to shear, usually named as dowel action (D. Santos & Pedro, 2009).

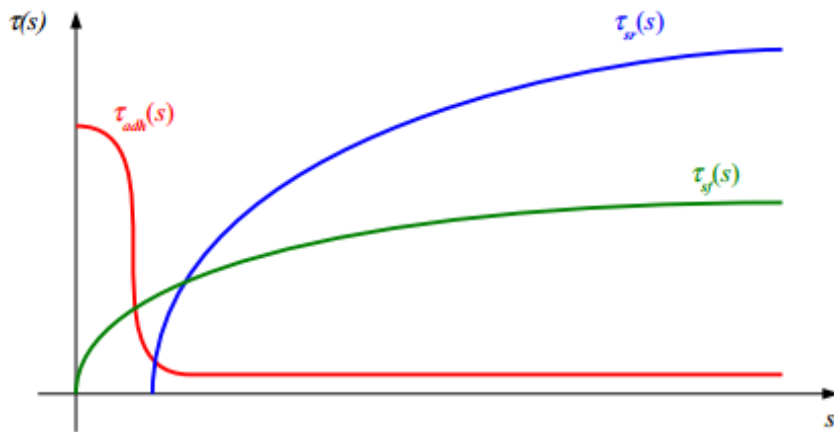


Figure 2-3 : Shear stress of concrete to concrete interface

The shear stress at a concrete-to-concrete interface, $\tau (s)$, for a given crack with a relative longitudinal displacement between concrete parts equal to s , is then given by:

The Failure Shear Stress was calculated by the following Equation

$$\tau(s) = \tau_{adh}(s) + \tau_{sf}(s) + \tau_{sr}(s) \quad \dots\dots\dots \text{Equation 2-1}$$

Where

- $\tau(s)$ -is shear stress at a concrete-to-concrete interface.
- $\tau_{adh}(s)$ -is the contribution of the adhesion
- $\tau_{sf}(s)$ -is the contribution of the shear-friction
- $\tau_{sr}(s)$ -is the contribution of the shear reinforcement for the shear stresses

2.2.1 Methods shear transfer strength

Three methods of computing shear transfer strengths have been proposed in the literature.

There includes:

- a) Shear friction models
- b) Cohesion plan friction models
- c) Horizontal shear models as occur in compline beams

In the modified shear-friction equation by Mattock:

$$V_n = K_1 A_{cv} + 0.8 A_v f_y \dots\dots\dots \text{Equation 2-2}$$

The first term ($K_1 A_{cv}$) represents the shear transferred by “cohesion”, which is caused by pieces of aggregate bearing on the surface of the slip plane, by shearing off of surface protrusions, and by dowel action. The second term represents the “friction” with the coefficient of friction taken to be 0.8 for cracked concrete sliding on cracked concrete.

2.3 Factors Affecting Shear Transfer

There are many factors affecting the shear transfer.

- Curing condition and difference in age between concrete layers
- Characteristic of concrete
- Characteristic of roughness
- Characteristic of reinforcement

2.3.1 Curing Condition and difference of age between concrete layers

The interface strength of concrete-concrete interface or reinforced concrete members with the part cast at different ages, is highly influenced by curing condition (Pedro Miguel Duarte Santos & Julio, 2011) two curing conditions were considered. one set of concrete specimens was stored in the laboratory and another set was stored outside, directly exposed to the environmental condition such as Solar radiation, rain and wind. They were cured for 112days. For the specimen shown in Figure 2-4 shrinkage measurement was done

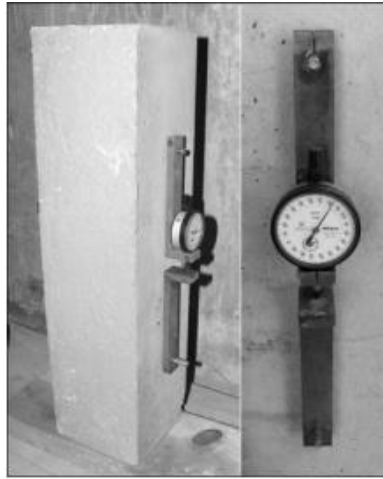


Figure 2-4: Concrete specimen for shrinkage measurements

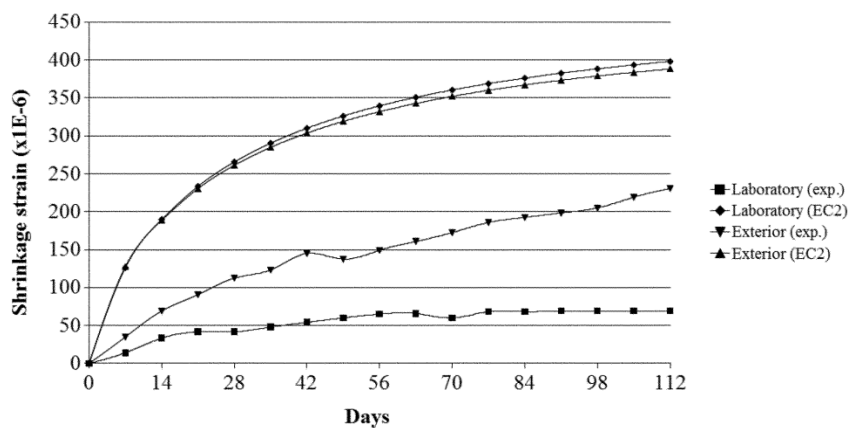


Figure 2-5: Evolution of concrete shrinkage strain (Pedro M.D. Santos & Júlio, 2014).

As shown in Figure 2-5 The shrinkage strain was higher for specimens stored outside due to environmental exposed and therefore these samples showed lesser shear capacity due to higher shrinkage.

For samples with maintenance the Experiment was tested with the following rehabilitation Methods as shown in Figure 2-6; Left as Cast (LAC); Wire Brushing (WB); Sand Blasting (SAB); Shot Blasting (SB); Hand- Scrubbing (HS) Cast with 28 Days:56 Days and 128 Days' time difference between old and new concrete.

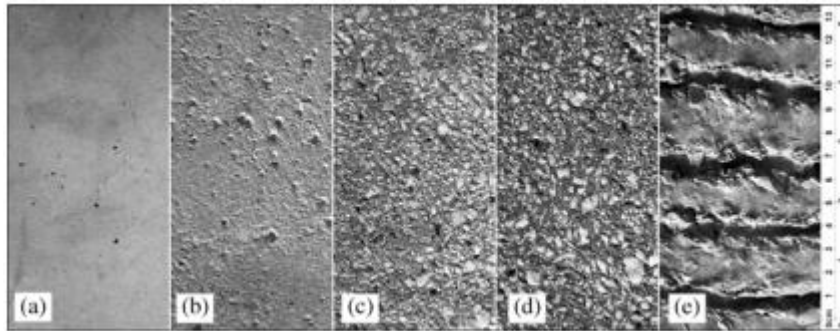


Figure 2-6: Surface preparation: (a) left as-cast; (b) wire-brushing; (c) sandblasting (d)shot blasting; and (e) hand-scrubbing;

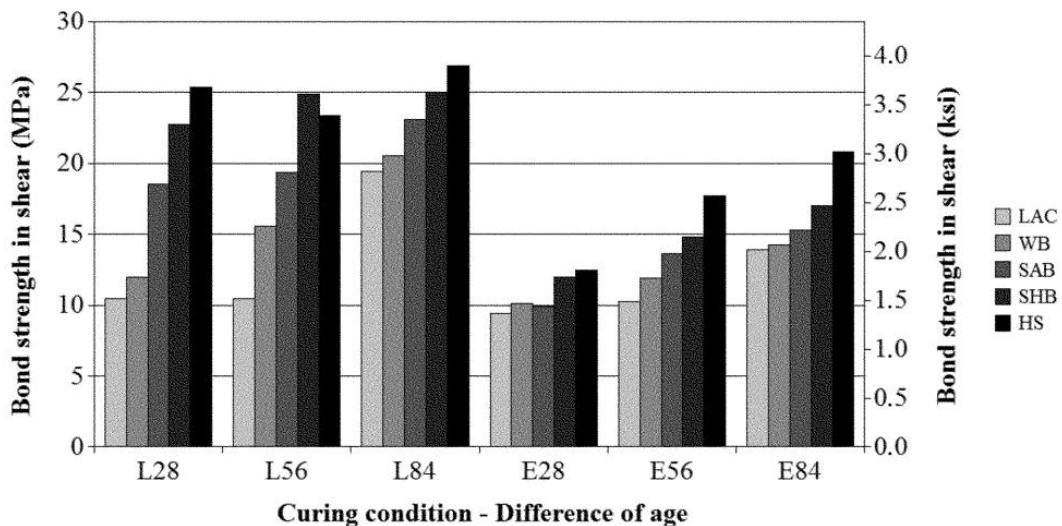


Figure 2-7: Bond strength for varying curing condition of interface(Pedro Miguel Duarte Santos & Julio, 2011).

The samples labeled “L” were stored in the laboratory and samples labeled “E” were stored outside on Figure 2-7. For shear strength because of high shrinkage strain bond strength in shear was lesser when curing outside.

Three different times were considered for the time gap between casting the substrate and the added concrete layer: 28, 56, and 84 days, with the aim of studying the effect of differential shrinkage between concrete parts. Six sets of specimens were produced: L28, L56, and L84 (L series); and E28, E56, and E84 (E series), where L reports to the specimens cured in the laboratory and E to those cured in the exterior of the laboratory,

followed by the difference of age, in days, between casting the substrate and the added concrete layer.

From above Figure 2-7 it can be observed that the pure shear Strength increases, for both curing conditions, with the increase of the difference of ages between the substrate concrete and the added concrete layer. (Pedro Miguel Duarte Santos & Julio, 2011)

From this research shrinkage stress was higher for specimens stored outside due to environmental exposed and therefore these samples showed lesser shear capacity due to higher shrinkage. Pure shear Strength increases with the increase of the difference of ages between the substrate concrete and the added concrete layer. They were studied by the slant shear test and splitting test for different cases of roughness of the substrate. But it more important to studies using direct shear strength test (Push off test) and direct tensile test method.

2.3.2 Characteristic of concrete

For cracked concrete, it has been shown that as the compressive strength of concrete increases the shear capacity of the interface also increases (Walraven, 1997) and (Mattock, 1969). However on a study conducted by (Mattock, 1969), he found that for a fixed amount of ρ_f (product of reinforcement ratio and yield strength of reinforcement crossing the interface) present across the interface, there is an upper value of concrete compressive strength in which concrete strength above that point would not enhance the shear capacity, But for compressive strength below this point, the shear capacity reduces. Form these researches as the compressive strength of concrete increases the shear capacity of interface also increase.

2.3.3 Characteristic of roughness

As the roughness of the interface increases, the adhesive bonding also increases (Pedro Miguel Duarte Santos & Julio, 2011). Different types of surface treatments were applied to an interface. The Roughening techniques studied were sand-blasting, chipping and steel brushing. A slant shear test was conducted to evaluate the Interface strength. The surface that was sand-blasted showed the maximum shear strength.

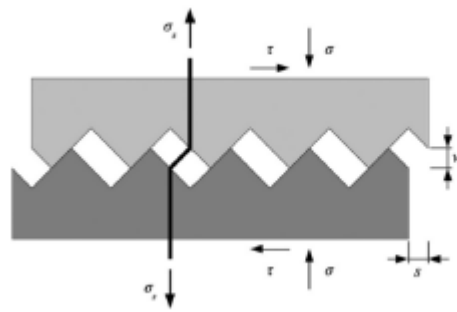


Figure 2-8: Frictionless saw tooth ramp model of friction mechanism (Pedro M.D. Santos & Júlio, 2014)

On another paper, the authors used digital image processing to quantify the roughness that is created by sand-blasting, wire brushing and as-cast surface (Pedro Miguel Duarte Santos & Julio, 2011). After capturing the surface profile, the authors used different criteria to quantify the roughness. It was shown that the interface bond strength was directly proportional to the amount of roughness parameter assigned.

Roughness also affects the amount of friction resistance developed between the surfaces. The roughness and a normal force perpendicular to the interface are the parameters that influence friction as can be seen in the shear friction formula.

The effect of roughness on dowel action was discussed. When the roughness of the interface increases, the specimen tends to split more than it slips. This transverse opening of the interface tends to put the reinforcement in tension rather than bending it. So, for a rough interface, dowel action may not be mobilized significantly before the failure of the interface. On the other hand, for a very smooth interface, slipping movement is dominant than splitting so the contribution of dowel action becomes significant.

2.3.4 Characteristic of reinforcement

- Reinforcement perpendicular to shear:

The reinforcement crossing the shear plane plays a major role in the shear transfer process. Amount of reinforcement, orientation of reinforcement, anchorage and whether the reinforcement is embedded in the concrete or tied externally are the factors that should be considered.

- Amount of Reinforcement:

The effect of the amount of reinforcement crossing shear plane was studied by (Mattock, 1969) for a monolithically cast concrete and for cracked concrete. Mattock found that when the amount of reinforcement is significantly high, cracked concrete shows similar behavior as the monolithically cast concrete.

So, in order to compare the effect of construction joints with monolithically cast concrete, the amount of reinforcement should not be high so as to not mask the effect of the construction joint.

- Orientation of reinforcement:

The effect of bar inclination was studied by (Walraven, 1997). He studied it for reinforcement embedded in concrete for a pre-cracked shear plane. He found that as the inclination increases, the shear strength of the interface decreases.

- Ways of placement of reinforcement:

In practical situations, reinforcement is placed inside concrete on shear planes. For research purposes, it is sometimes desirable to place the bars externally. This is because when the reinforcement is embedded, accurately measuring the strain of the reinforcement becomes a challenge. In addition, the bond property between concrete and reinforcement might vary for the different samples. Placing the bar externally helps to avoid this constraint.

Bars are also placed externally in order to eliminate the effect of dowel action to study the shear transfer mechanism of concrete. (Walraven, 1997) applied this method of specimen preparation and confirmed it reduces the dowel effect to a negligible value (Figure 2-9). (Walraven, 1997) also tried to eliminate the effect of dowel action by placing a rubber sleeve around the reinforcement inside the concrete.

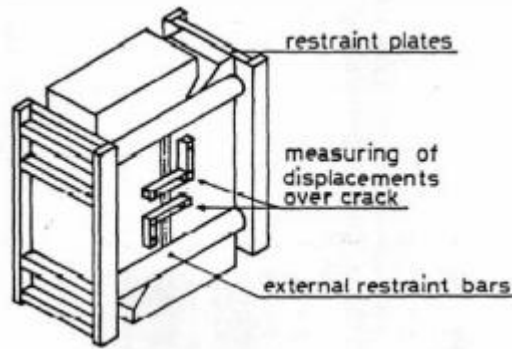


Figure 2-9: Arrangement of restraint plates and bars on the specimens (Walraven, 1997).

- Reinforcement parallel to the shear plane:

Reinforcement parallel to and found in the vicinity of the shear plane contributes to the shear transfer strength. An analysis based on the truss model with softened compression stress-strain relation for concrete was used to analyze shear transfer strength in initially un-cracked concrete. A critical zone was identified and analyzed. With this, the contribution of reinforcement parallel to the shear plane was shown.

2.4 Interface Tensile Strength

There are different types of tests to determine concrete tensile strength. Splitting test, flexural test and uniaxial direct tensile test. The tensile strength of concrete is much lower than the compressive strength, largely because of the ease with which cracks can propagate under tensile loads. Flexural and splitting strengths was higher than direct tensile strength. Flexural strength also gives higher value than splitting test. This is summarized by the following, Flexural strength \succ Splitting strength \succ Direct tensile strength as shown in Figure 2-10.

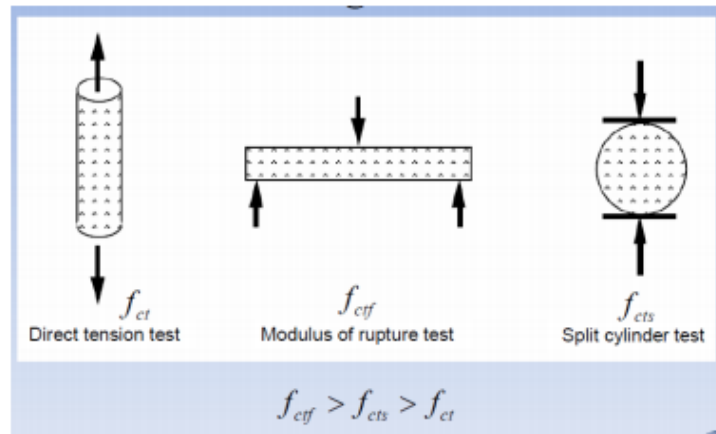


Figure 2-10: Different types of test for concrete tensile strength

Using splitting tensile test tensile strength test (Pedro M.D. Santos & Júlio, 2014) was conduct experiment on tensile strength. The test method was splitting test as shown in Figure 2-11.

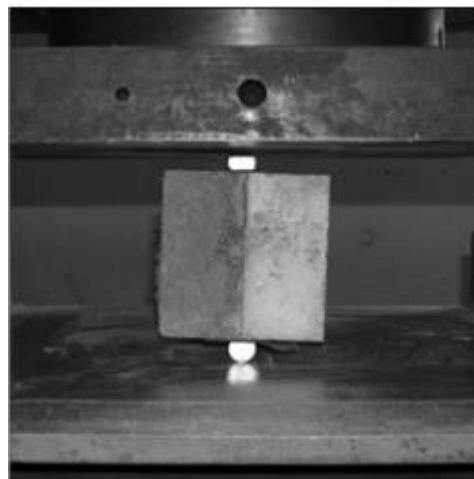


Figure 2-11: Splitting test for interface tensile strength

As shown in Figure 2-12 the interface tensile strength increases with increase roughness of substrata layer. Furthermore, as the age of casting between old and new concrete was increases the interface tensile strength was also increase.

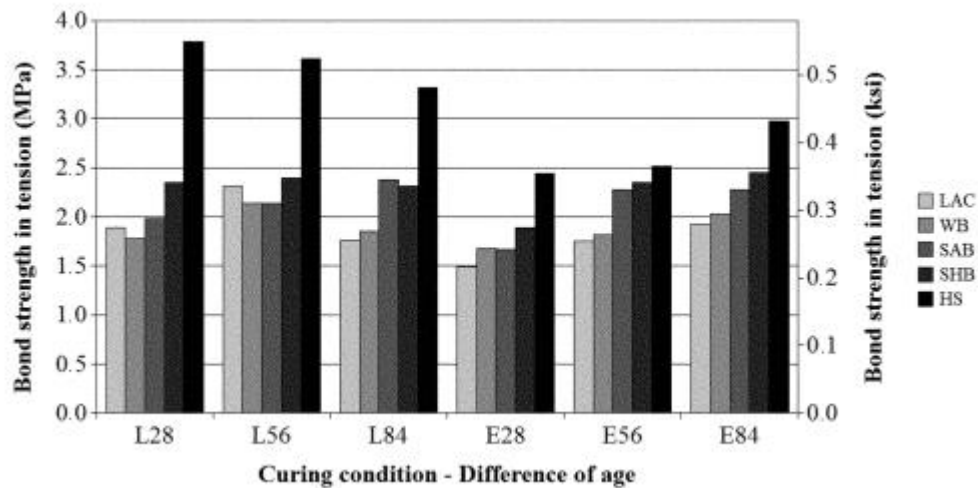


Figure 2-12: Tensile Bond strength for varying curing condition of interface (Pedro Miguel Duarte Santos & Julio, 2011)

2.4.1 Different Type of Direct Tensile Method

Direct tension method can more realistically predict the tensile Strength and ductile behavior (Qiao & Zhou, 2018). There are different types of tensile bond strength tests.

1. Notched beam with cylinder

- Some fractures still do not occur at the notch
- Local stress concentration caused by the notch, cannot accurately predict the tensile strength.

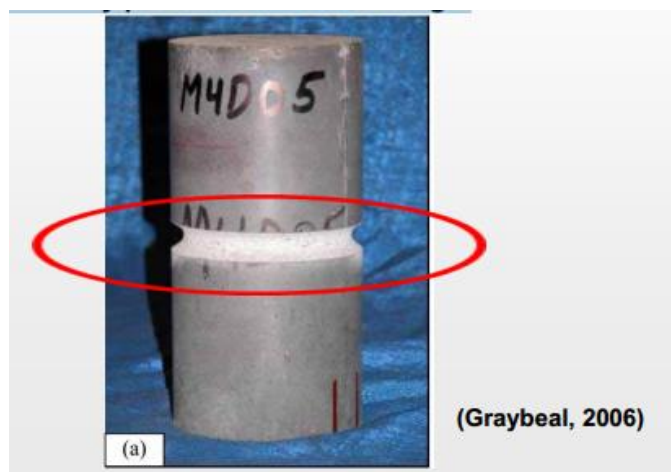


Figure 2-13: Notched beam with cylinder (Graybeal, 2006).

2. Un notched beams or cylinders

- High requirements of grip system
- Stress concentrations at ends, fractures occur beyond to the gauge length of LVDTs

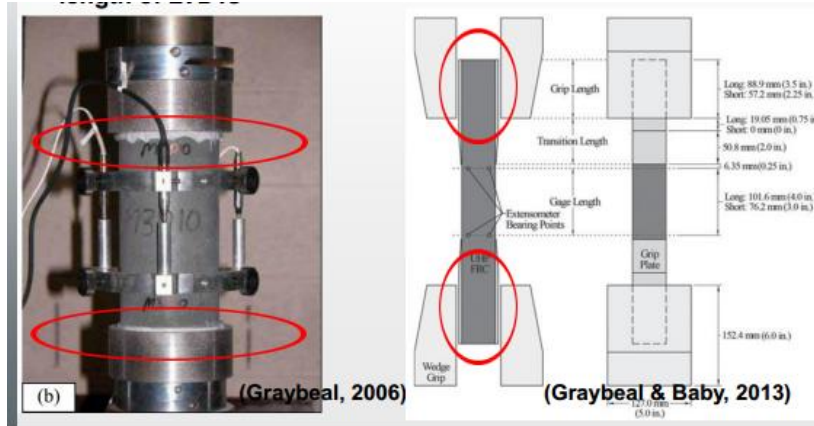


Figure 2-14: Un notched beam with cylinder (Graybeal, 2006).

3. Dog-bone shaped mold

- Easily grip and avoid stress concentration
- Constant section area and tensile stress at middle part.
- No standard test protocols.

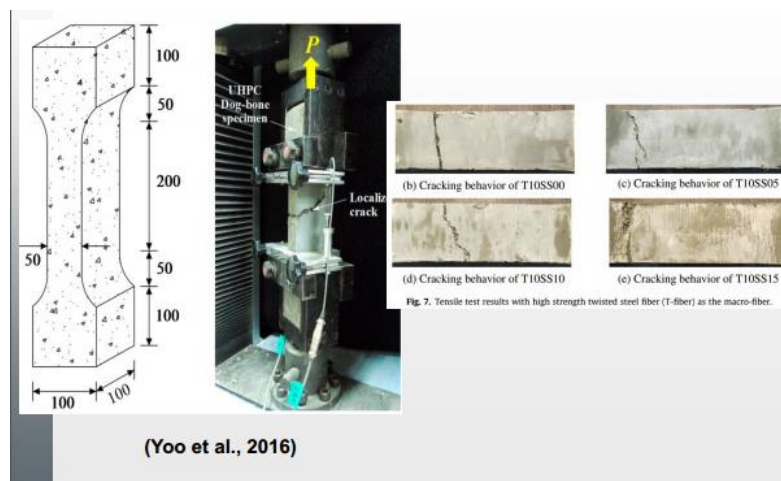


Figure 2-15: Direct tensile test with dog bone mold.

From these researches although it is very difficult to determine direct tensile strength of concrete but direct tension test can more realistically predict the tensile strength and ductile behavior of concrete.

2.5 Surface Profile Evaluation

In order to compute the surface roughness parameters such as R_a the surface profile has to be mapped. For this purpose, numerous machines were produced and use in various fields especially in industry. According to American National Standards Institute (Bogdan, 1985), the methods for measuring roughness and surface texture can be classified into three types: contacting methods, taper sectioning, and optical (non- contacting) methods.

2.5.1 Mechanical Profilometry

The deviations of surface geometry are detected by a sensor (stylus) that moves along the surface. The gauge turns the vertical deflection of the stylus as a function of position into the electrical signal which is registered by the computer and in the end, a surface profile is obtained as shown in Figure 2-17. There is a possibility of regulation of the distance between measurement points to get better precision. Geometry (round or conical) and size (radius) of the stylus extremity are of prime significance for real profile restitution because, some profile of small wavelengths will not be registered if the diamond cone radius is too large (Figure 2-16).



Figure 2-16: Two types of profilometer styluses(Courard, Bissonnette, & Garbacz, 2015).

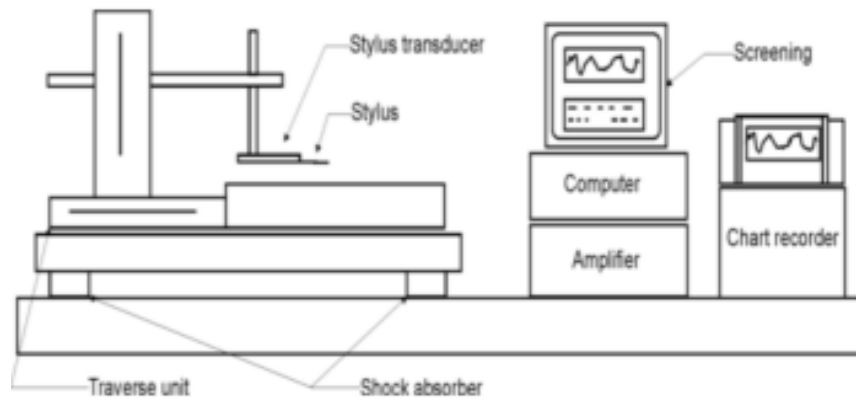


Figure 2-17: Scheme of mechanical profilometer device(Courard et al., 2015).

2.5.2 Laser Profilometry

Laser profilometry method is based on a laser distance measurement by optical displacement meter. In this technique, a principle referred to as optical triangulation. Optical triangulation uses a light source (commonly a diode laser), imaging optics, and a photodetector. As shown in Figure 2-19, a diode laser is used to generate a collimated beam of light, which is then projected onto a target surface. A lens focuses the spot of reflected laser light onto a photodetector, which generates a signal that is proportional to the spot's position on the detector.

As the target surface height changes, the image spot shifts due to the parallax. To generate a three-dimensional image of the part's surface, the sensor scans in two dimensions, generating a helical set of radius data that represents the inside surface topography of the tube. Software then generates a color image of the inside surface of the tube. The idea is taken from an old comb method and it is very simple but instead of the needles there is an emitter of a laser signal moving along the surface and measuring distance to the surface, Figure 2-18.

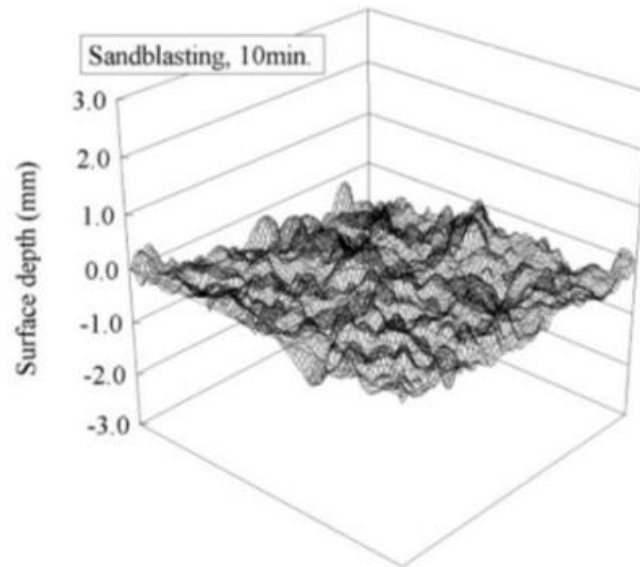


Figure 2-18: Result screen of laser profilometry (Courard et al., 2015).

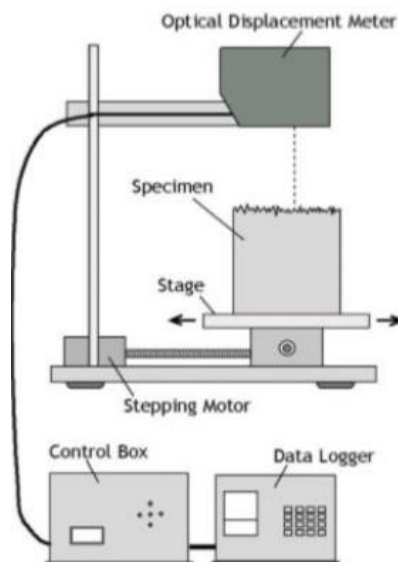


Figure 2-19: Laser profilometry equipment (Courard et al., 2015).

2.5.3 Opto-morphology

The above presented two profilometry methods are used only in laboratory conditions (Courard et al., 2015). Recently, works are focused on development optic-based methods which can be used in site. The moiré projection technique which belongs to an interferometrical measurement method can be considered as the technique useful for this

purpose. The moiré phenomenon appears when two networks of light rays, made of equidistant lines alternatively opaque and transparent are superimposed. The technique of identification of relief is based on the deformation's measurement of a parallel fringes pattern projected on a surface, Figure 2-20.

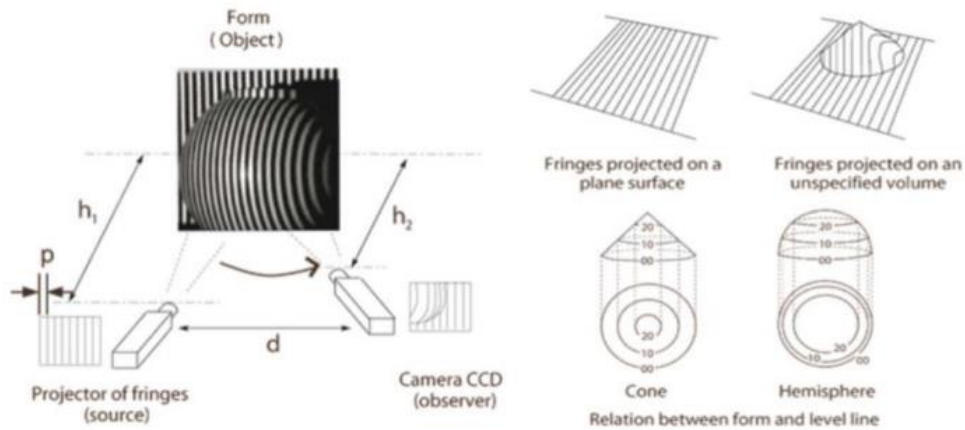


Figure 2-20: Moiré projection principle (Courard et al., 2015).

2.6 Previous studies' results of concrete over layer Interface strength

This paragraph presents the main previous studies results in this field. These results contain; compression strengths for both substrate and repair material surfaces roughness coefficient R_a , Interface shear strength and interface tensile strength in Table 2-1.

Table 2-1: Previous studies result.

Reference		Perez et al,2009			Santos et al,2006		
Compressive Strength	Substrata	33.00			46.22		
	Repair material	32.00			50.40		
R_a and Interface strength		Ra	Interface Shear strength	Interface Tensile strength	Ra	Interface Shear strength	Interface Tensile strength
			MPa	MPa			
		0.240	5.70	2.60	0.031	1.30	0.00
		0.460	5.90	2.40	0.099	10.67	1.92
		-	-	-	0.203	14.13	2.65

CHAPTER 3 EXPERIMENTAL PROGRAM

3.1 Choice of the Specimen

The object of this research is to investigate interfacial shear strength and interfacial tensile strength between old and new concrete at different moisture condition. The Interface strength between the repair material and old concrete substrata is tested using two interface strength tests, push-off test for shear and direct tensile test for tensile test. Wide ranges of specimens were prepared and tested.

3.2 Material

For manufactured concrete fine aggregate, coarse aggregate, cement and water was used. The target mean cubic compressive strength was 40MPa. The materials was prepared and tested in Construction Material Laboratory in Addis Ababa Institute of technology.

3.2.1 Fine Aggregate

To remove the excess silt, the material used in the experiment was also washed. The final content of silt has been reduced to about 2%. The sand was stored in a plastic bag until the time of mixing to maintain the moisture content of the coarse aggregate. The properties of sand used are presented in Table 3-1.

Table 3-1: Properties of fine aggregate used.

No	Test description	Test result
1	Silt content	1.67%
2	Moisture content	1.57%
3	Absorption	3.09%
4	Fineness modules	2.89%
5	Dry unit weight (kg/m ³)	1574.00
6	Bulk (Dry) specific gravity	2.478
7	Bulk (SSD) specific gravity	2.564
8	Apparent specific gravity	2.690

3.2.2 Coarse Aggregate

The coarse aggregate was washed to reduce the silt content. Since the aggregate was not well graded, it was sieved after washing it and the sieving was done using 25 mm, 19mm, 12.5mm, 9.5 mm and 4.75mm sieve sizes. The sieved aggregate was then mixed according to the standard of ASTM as shown in Table 3-3 and stored in a plastic bag until the time of mixing to maintain the moisture content. Physical tests of the aggregate were conducted and are presented in Table 3-2 and Table 3-3. The coarse aggregate was well-graded as shown in the PSD graph as shown in Figure 3-1.

Table 3-2: Properties of coarse aggregate used.

Material property	Coarse aggregate
Gradation	Well-graded
Dry unit weight	1555 kg/m ³
Absorption	1.56%
Specific gravity	2.64%
Nominal aggregate size	25 mm

Table 3-3: Sieve analysis of coarse aggregate.

Sieve size	Weight retained	Percentage retained	Cumulative coarse	Cumulative passing	Standard passing
mm	Kg	%	%	%	%
37.5	-	-	-	100	100
25	0	5	5	95	90-100
19	0	25	30	70	40-85
12.5	0	45	75	25	10-40
9.5	0	16	90	10	0-15
4.75	0	10	100	0	0-5
Pan	0	0	100	-	0
Total		100	295	-	-

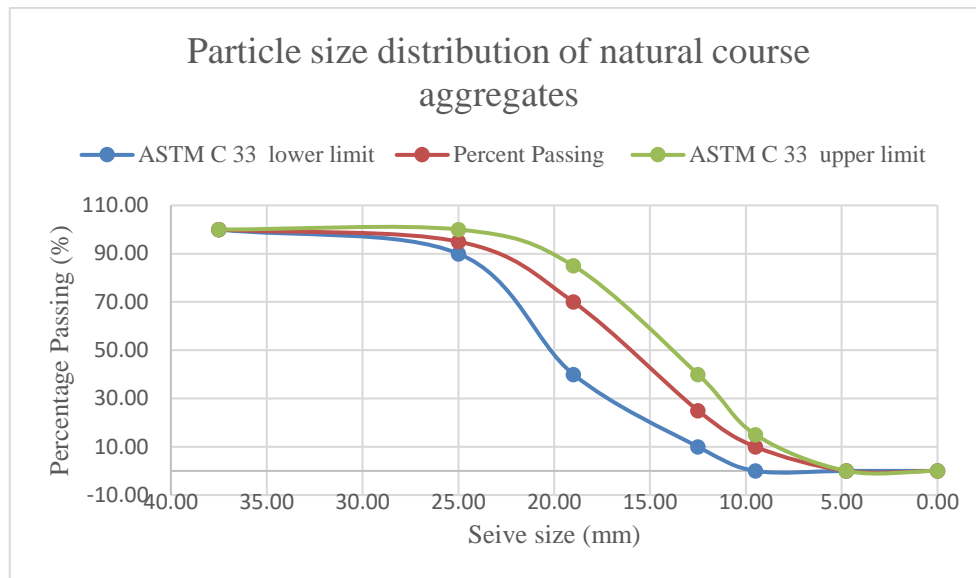


Figure 3-1: The PSD curve for natural coarse aggregate.

3.2.3 Cement

An ordinary Portland cement was used for all specimens.

Table 3-4: Cement properties used.

Factory	Dangote cement factory
Product type	Ordinary portland cement
Strength class	42.5R
Standards	ES EN-197-1-2012

3.2.4 Concrete

In the preparation of concrete, great care was taken to preserve a consistent mechanical property for all specimens. The target mean strength was 40MPa. After adjustment, concrete was used mass per cubic meter. For all samples, relatively similar concrete strength was achieved. the mix was done using ACI mix method and the following proportions were finally obtained after many trails.

Table 3-5: Mix properties per cubic meter of concrete.

Material type	Mass (kg)
Gravel	1007.00
Sand	797.42
Cement	295.08
Water	190.00
Water to cement ratio	0.61
Coarse aggregate to sand ratio	0.45

Table 3-6: Coarse aggregate mixing ratio.

Materials	Mass (kg)
25.0 mm	50.35
19.2 mm	251.75
12.5 mm	435.15
9.5 mm	151.05
4.75 mm	100.7
Sum	1007.00



Figure 3-2: Mixing of concrete.

3.2.5 Reinforcement

3.2.5.1 Reinforcement Confining the Interface

For the externally passed (placed) reinforcement, dia.14 plain bars were used. The reinforcing bars had 304 MPa yield strength and ultimate strength of 420 MPa. The bar was used for external confinement when push-off samples were tested. The properties of reinforcement used are presented in Table 3-7.

Table 3-7: Properties of reinforcement bar used (plain round bar)

Material Property	Plain bar (dia. 14)	Plain bar (dia. 14)
Reinforcement Diameter (mm)	14.000	14.000
Cross-Sectional Area (mm ²)	153.938	153.938
Yield Force (KN)	45.600	48.600
Yield Strength (MPa)	296.223	313.438
Ultimate Force (KN)	65.250	64.320
Ultimate Strength (MPa)	423.872	423.872
Original Length (mm)	200.000	200.000
Change in Length (mm)	40.000	45.000
Elongation (%)	20.000	20.000
Mass of Sample (kg)	1.025	1.036
Length of the Sample (mm)	0.815	0.815
Unit Weight (kg/m)	1.258	1.271



Figure 3-3: Testing tensile strength of bar used.

3.2.5.2 Reinforcement inside the Concrete

The reinforcement inside each part of the push-off sample concrete was needed to carry tensile stress at indicated locations, but it has no influence on the interface behavior. A dia. 10mm deformed reinforcing bar with a yield strength of 511 MPa and ultimate strength of 611 MPa was used as transversal reinforcement. Another type of reinforcement used as longitudinal reinforcement in the shear specimen was a dia.16mm deformed bar with a yield strength of 544 MPa and ultimate strength of 638 MPa. The properties of reinforcements used in the specimens are presented in Table 3-8.

Table 3-8: Properties of reinforcement bar used (deformed bar).

Material Property	<i>Deformed bar (dia. 10)</i>	<i>Deformed bar (dia. 16)</i>
Reinforcement Diameter (mm)	10.000	16.000
Cross-Sectional Area (mm ²)	78.540	201.062
Yield Force (KN)	40.200	109.50
Yield Strength (MPa)	511.842	544.608
Ultimate Force (KN)	48.000	128.4
Ultimate Strength (MPa)	611.155	638.609
Original Length (mm)	200.000	200.000
Change in Length (mm)	13.000	10.000
Elongation (%)	6.500	5.000
Mass of Sample (kg)	0.38	1.24
Length of the Sample (mm)	0.600	0.810
Unit Weight (kg/m)	0.633	1.531

3.3 Specimen Preparation and Casting

3.3.1 Mold Preparation

3.3.1.1 Push off Mold and Reinforcement Detailing

The push-off shear test was carried out to assess the strength of the interface in shear. The adopted geometry for shear specimens was a 125x250x540 mm³ prism as shown in Figure 4-3. The mold was previously used in (Zerbruck, 2015) and (Solomon, 2018).

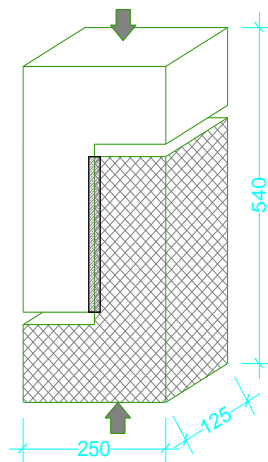


Figure 3-4: Specimen dimensions

The reinforcement detail is shown in for inside each part of the push-off sample concrete was needed to carry tensile stress at indicated locations, but it has no influence on the interface behavior.

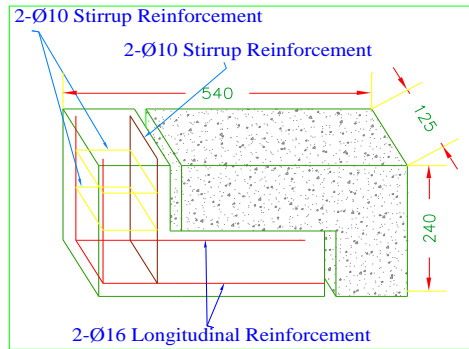


Figure 3-5: Rebar detailing of shear specimens (all dimensions are in mm unit).

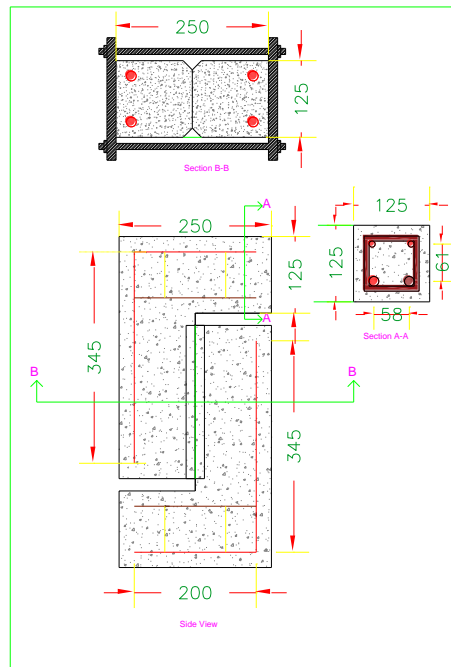


Figure 3-6: Rebar detailing and push of mold (all dimensions are in mm unit).

3.3.1.2 Dog-Bone Mold

The dog bone mold for direct tensile test specimens was cast in a metal formwork specifically manufactured for this purpose. The adopted geometry defined for the dog bone tensile specimens was 150x150x500 mm. Due to stress concentrations at the ends of the specimen, fractures occur beyond the gauge length and it did not predict the direct tensile strength. The mold was specially manufactured to avoid stress concentration at the top and bottom of the specimen. The cross-section of the specimens starts with 150x150mm at top and bottom, and changes to a prismatic shape of 100x150 mm after 25mm reduction of width in both sides as shown in Figure 3-8. To avoid failure at the sharp corner where the cross-section changes, the mold was prepared with two different curves. The first curve has a 25mm radius from the internal face and the second curve has a 51mm radius from the external face of the mold. The transition zone of the cross-section has a total of 50mm length.

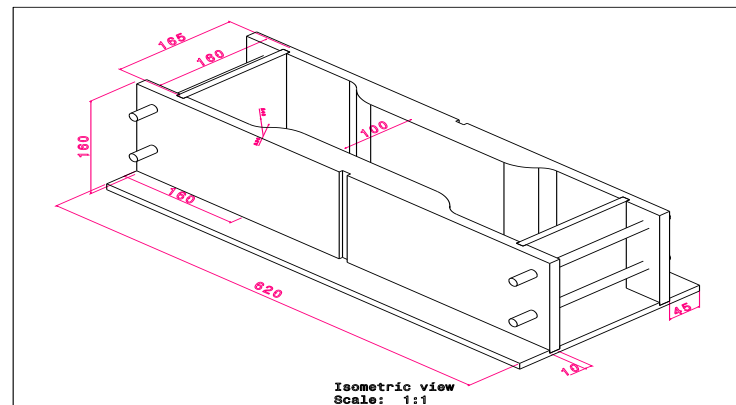


Figure 3-7: Dog-bone specimen.

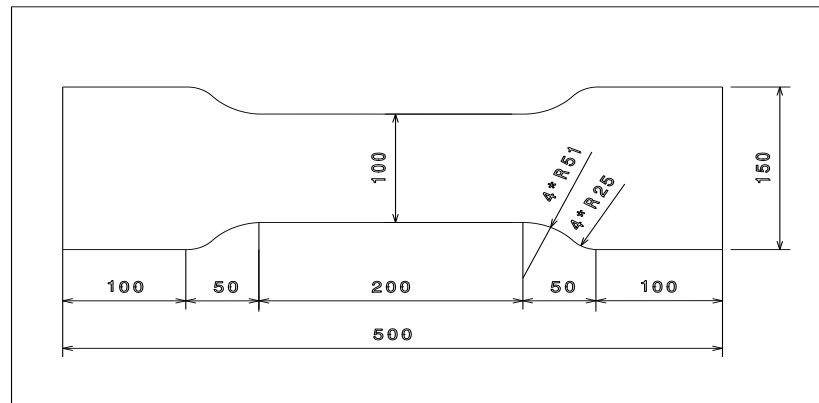


Figure 3-8: Plan drawing of dog-bone.

3.3.2 Preparing Shear Push-off Samples

3.3.2.1 *Preparing of Substrata (Old Concrete) Structure and roughness of the interface*

The formwork was first assembled and oiled to facilitate the removal of the metal plate. Concrete was mixed and cast half of the push-off mold. After 24 hours these specimens were removed from the mold and left under curing for 28 days. The roughness of the shear was left as cast.



Figure 3-9:Placing of reinforcement.



Figure 3-10:Substrata structure after remove from the mold.

3.3.2.2 Repairing Material Placement

For variable sample (sample cast with interface) after curing for 28 days, specimens were removed from the water and left under room temperature for 24 hours. The old substrata concrete was put to push-off mold and the new concrete was cast. Great care was taken for the consistency of the roughness of concrete. No treatment or bonding agent was used to the time of adding repair material.

3.3.2.3 Specimen Designation and Compressive Strength for Shear

The average compressive strength test results are presented in Table 3-9. Furthermore, the detailed results of the compressive strength test are provided in APPENDIX A.

To check and control the consistency of samples a compressive strength test was done. For monolithically cast sample 9 mixes were done and mean compressive strength of 39.41MPa was achieved with a coefficient of variation 6.67%. For cast with interface sample, 22 mixes were done and a mean compressive strength of 34.85MPa was achieved with a coefficient of variation 12.94%. Therefore, from both cases, average compressive strength of 36 MPa was achieved with a coefficient of variation of 12.28%.

Table 3-9 shows the specimen designation and cubic compressive strength for monolithically cast specimens. The specimens are designated with three letters. The first letter “M” indicates that the specimens are monolithically cast. The second letter indicates the type of test “S” indicates the specimen is tested for Shear. The third letter indicates “D” the specimens were tested in the dry or wet condition. The letter indicates “W” the specimens were tested in the wet environmental condition

Table 3-9: Cube Compressive strength result for monotonically cast samples.

Designation	Compressive strength (MPa)
MSD-1	41.565
MSD-2	44.232
MSD-3	38.965
MSD-4	37.757
MSD-5	36.920
MSW-6	38.028
MSW-7	39.227
MSW-8	41.820
MSD-9	36.160
COV	6.67%

Table 3-10 shows specimen designation and cubic compressive strength for cast with an interface. For letter “ISD” indicates Cast with interface sample Shear test at Dry environmental condition. Furthermore “ISW” Cast with interface sample shear test at wet environmental condition.

Table 3-10: Cube Compressive strength result for cast with interface samples.

Designation	Compressive strength (MPa)	
	Substrata	Overlay
ISD-1	43.077	29.525
ISD-2	35.968	33.333
ISD-3	45.144	29.033
ISD-4	41.492	29.820
ISD-5	39.682	35.440
ISD-6	39.682	35.440
ISW-7	32.922	34.240
ISW-8	35.993	31.284
ISW-9	34.158	38.295
ISW-10	39.384	41.820
ISD-11	33.200	36.820
COV	10.84%	17.38%

3.3.3 Direct Tension Specimen

3.3.3.1 *Preparing of Substrata (Old Concrete) Structure and Roughness of the Interface*

The dog bone formwork was first assembled and oiled to facilitate the removal of the metal plate. Concrete was mixed and cast half of the dog bone mold. In order to create similar roughness with shear samples the mold was cast vertically. After 24 hours these specimens are removed from the mold and left under curing for 28 days. The roughness of the shear sample was left as cast and vibrated.



Figure 3-11:Dog-bone mold



Figure 3-12:Cast of old concrete

3.3.3.2 *Repairing material placement*

A similar procedure was followed from shear sample but with different mold (dog bone shape mold for the direct tensile test)



Figure 3-13: Surface roughness at tension zone.



Figure 3-14: Casting of new concrete

3.3.3.3 *Specimen Designation and Compressive strength and Splitting Test for Tension*

The average cubic compressive strength test results are presented in Table 3-11 and Table 3-12. Furthermore, the detailed results of the compressive strength test are provided in APPENDIX B. The description MTD indicates Monolithically cast, Tensile loading type at Dry environmental condition. At the time of testing the rate of loading was 0.28 MPa/s for cube testing machine and manually for splitting tensile machine.

Table 3-11: Compressive strength and splitting tensile strength result for Monolithically cast Specimen.

Designation	Compressive strength (MPa)	Splitting tensile strength (MPa)
MTD-1	43.077	3.856
MTD-2	29.525	3.065
MTD-3	35.968	3.839
MTD-4	33.333	3.956
MTD-5	45.144	3.579
MTD-6	29.033	3.752

The description ITD indicates Cast with interface, Tensile loading condition at dry environmental condition.

Table 3-12: Compressive strength and splitting tensile strength result for cast with interface samples.

Designation	Compressive strength		Splitting tensile strength	
	Substrata (MPa)	Overlay (MPa)	Substrata (MPa)	Overlay (MPa)
ITD-1	43.077	29.525	3.856	3.065
ITD-2	35.968	33.333	3.839	3.959
ITD-3	45.144	29.033	3.579	3.752



Figure 3-15: Strength test machines a) cylindrical splitting tensile(left) and b) cubic compressive strength(right).

The shear and tensile strength test were summarized by the flow chart in Figure 3-16. As shown in the flow chart specimens were prepared for shear strength and tensile strength tests. On the flow chart “control” means samples cast without interface. “interface” means sample cast with the interface at old and new concrete. For shear samples tests were done by varying environmental conditions and confinement strain. For tensile samples, they were tested only dry environmental condition. For cast with interface cast sample, they were tested using direct tensile test and for monolithically cast samples they were tested by using splitting tensile strength test and converted to direct tensile strength using the numerical equation from previous studies.

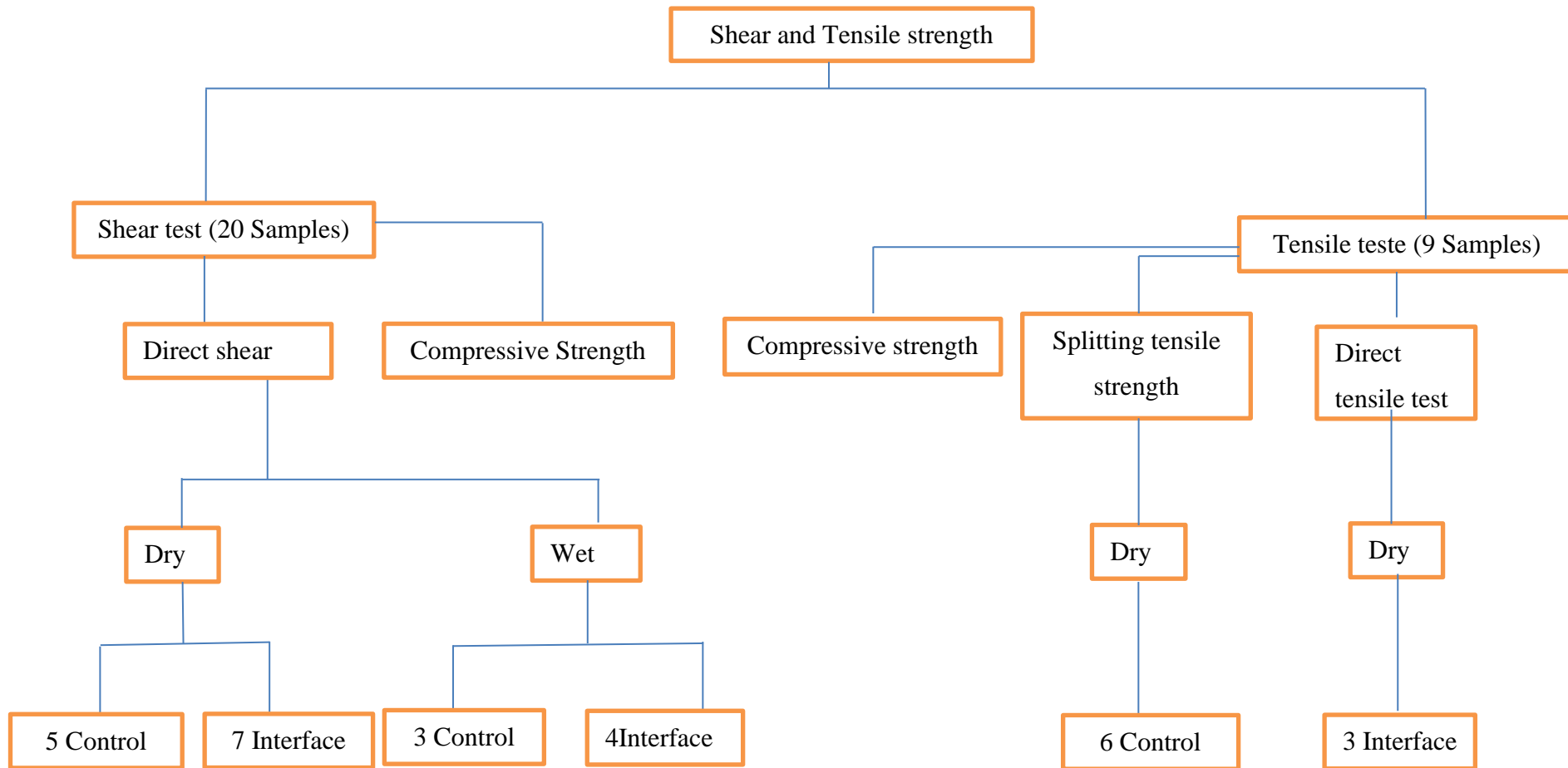


Figure 3-16: Flow chart of test program.

3.4 Test Setup and Instrumentation

3.4.1 Test setup and Instrumentation for Shear Test

The instruments used in the experiment were, strain gauges of concrete and steel, data logger, hydraulic jack, transducer and Pi-displacement transducer. one element strain gauge strain gages were attached to external confinement reinforcement at its middle length to obtain the strain of external confining strain. A load cell was located at the end of the specimen to measure the load at desired intervals together with other data. A hydraulic jack was used to apply loads. Pi-shape displacement transducer was used to measure the opening of concrete. Displacement transducer was used to measure relative displacement between two L shaped specimens. Data logger TDS-630 was used for an electric signal which presented in display the result. a data logger is an electric device that records data over time.

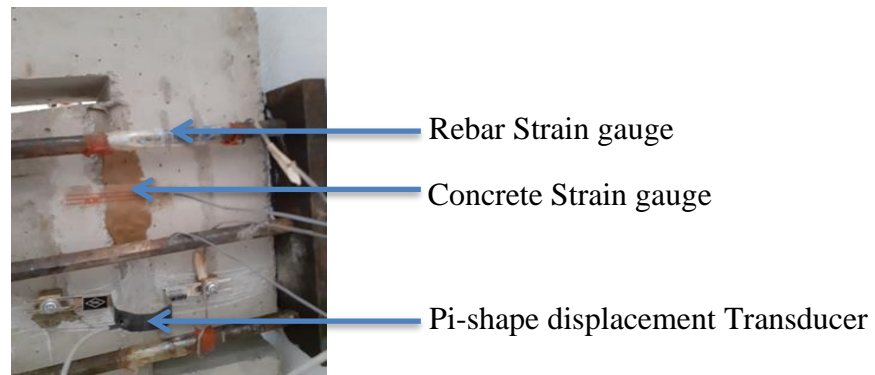


Figure 3-17: Strain gauge and Pi shape displacement transducer.

3.4.1.1 Test set up for Dry Environmental condition

A trial test was done necessary to come up with an acceptable test up and instrumentation to study. After curing the specimen was left from curing tanker and exposed to dry environmental condition. Then the sample was attached to the side, top and bottom plates using epoxy resin.



Figure 3-18: specimen after curing and epoxy.

After 24 hours of applying the epoxy, initial confining stress was applied by tightening the bolts on the confining bars. A confining strain was initially provided for specimens (i.e. without confining strain, $100\mu\epsilon$, $125\mu\epsilon$). Initially, roller support at top and bottom was used at first trial and it became unstable. And at second trial roller support was provided at the bottom of the specimen and 2cm wide plate was provide at top and this support condition was used for all samples. Styrofoam was placed at the sides of the push-off specimen to keep it stability. Then the specimen was tested by applying manually using hydraulic jack.

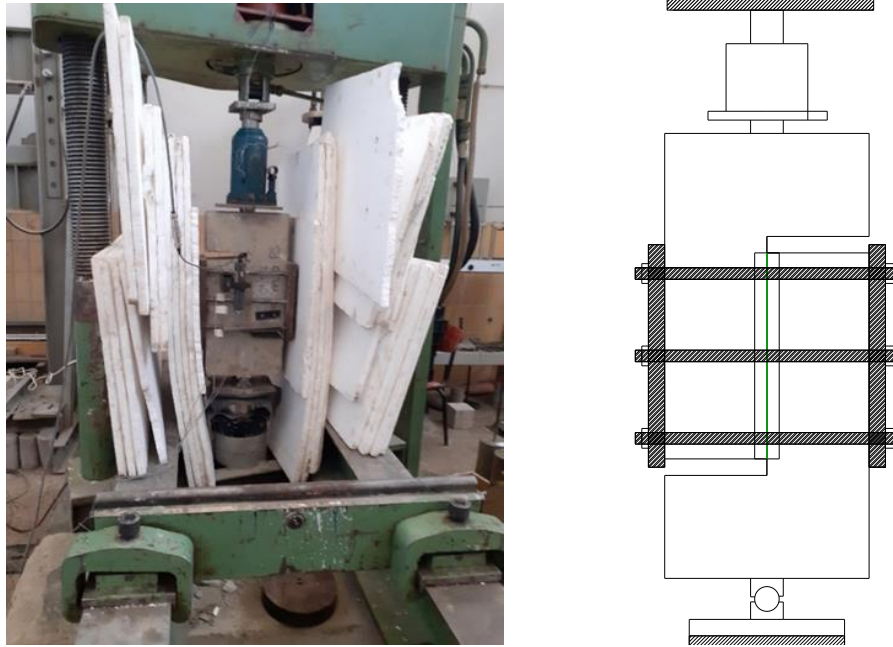


Figure 3-19: Dry environmental condition testing set up.

3.4.1.2 Test set up for wet Environmental condition

To test the interface in a moist condition, the sample was submerged under water for 24 hours in order to enter the water for pores of concrete. A custom tanker was manufactured. The tanker was constructed of metal sheet except for one face of the tanker which was made to be a transparent glass to monitor the specimen while testing. The load cell was placed under the tanker to measure the load being applied. Special care had to be made to place the tanker at the center of the load cell to avoid overturning of the whole set up (Figure 3-26). The bottom plate on which the round roller bars rest on was welded to the bottom of the tanker to avoid slipping of the specimen in water. Another challenge was to keep the Styrofoam in place when the water was filled. The Styrofoam was pushed up by the buoyancy force of the water. Restraining wires were placed outside the tanker to keep the Styrofoam in place. Another concern was the functionality of the strain gauges under water. Even though the wires of the strain gauges are coated, gasket maker was placed on the wires to keep water from entering and creating a short circuit.

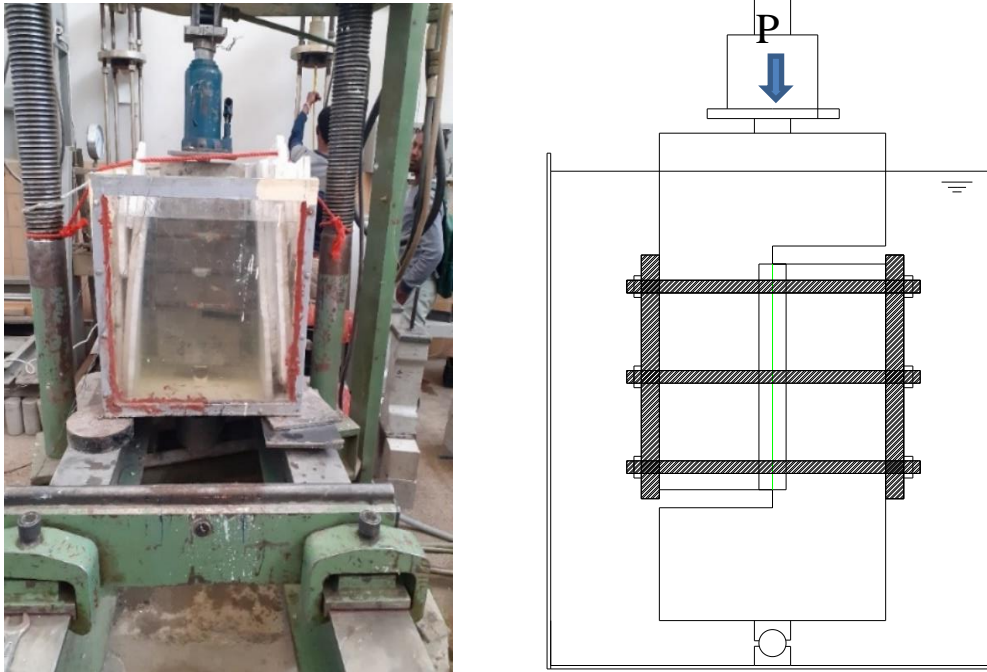


Figure 3-20: Wet environmental condition test set up

3.4.2 Test Setup and Instrumentation for Tensile Test

The instrument used in the experiment were a center hole jack machine, testing frame Transducer, Data Logger and Concrete Strain gauges, Endplate with a steel rod.

Preparation of the test involved End plates connected to 20 mm dia steel rod. The two endplates were glued at each end of the specimen using epoxy resin. Applied epoxy resin for 72 h prior to the test to reach ultimate strength for both the bottom and top side of the spacemen. as shown in Figure 3-21.



Figure 3-21: Attaching plates to the sample with epoxy (a) bottom epoxy (b) top epoxy (c) testing frame.

Two displacement transducers were mounted on opposite sides of the specimen to measure displacement along the length of the narrow cross-section. Concrete strain gauge was attached on the face of the specimen. Then the specimen was placed on the steel frame. The support condition was fixed vertically at bottom and fixed at top using the grip by the center hole jack machine. After connecting displacement transducer wires and strain gauge wires with the data logger. Tensile load was applied using center hole jack. Testing setup of the tensile specimen as shown in Figure 3-22.



Figure 3-22: Direct tensile setup using center hole jack.

3.5 Test set up for Mapping surface profile

The deviation of surface geometry was detected by a displacement transducer. The accuracy of the vertical transducer was 0.02mm and a resolution of 0.01mm. the vertical transducer turns the vertical deflection of the transducer as a function of position into an electric signal which presented in display in datalogger. The milling machine surface can move horizontally in X, alongside Y and vertically in Z-direction as shown in Figure 3-23. So, first, the displacement transducer was attached to the milling machine using a magnet as shown in Figure 3-24. After that, the alongside and vertically of the surface of the failed specimen was fixed at the center of the rough surface. by fixing the location of the transducer, the specimen was slowly moved horizontally using the milling machine. horizontal positions X and elevations Z ware recorded. Finally, the recorded data were analyzed using an excel datasheet. Furthermore, a surface profile was obtained using the X vs Z graph.

The profile reading, X and Z, are recorded manually (from data logger) in the template were prepared for this purpose. The measurement set up was shown in Figure 3-23 and Figure 3-24.

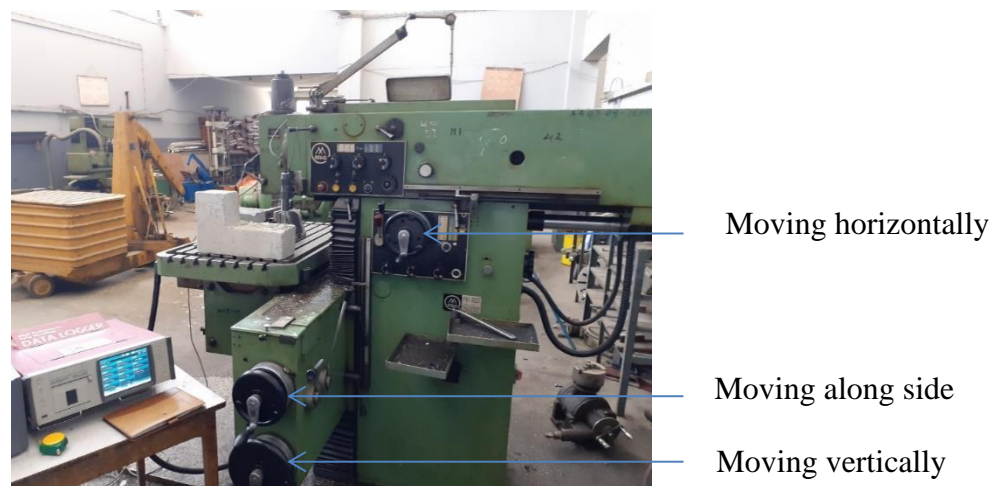


Figure 3-23: Roughness measured using displacement transducer and milling machine.



Figure 3-24: Measuring depth using displacement transducer.

CHAPTER 4 EXPERIMENTAL RESULT AND DISCUSSION

In this chapter, the experimental results accompanied by the discussion are presented. The result of the experimental program was compared for interface shear resistance, interface tension resistance and surface roughness change for monolithically cast and cast with interface samples.

4.1 Results of Tests for Shear

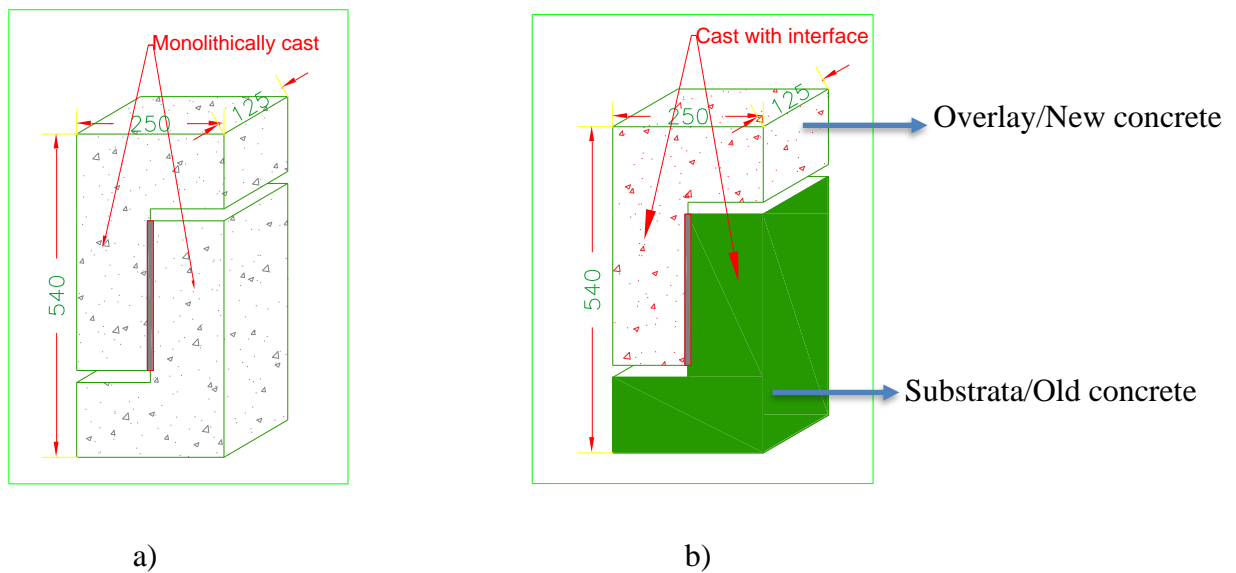


Figure 4-1:(a) Monolithically cast (b) Cast with interface samples

For this thesis, a total of 20 push-off specimens were tested, of which 11 specimens were cast with an interface and 9 specimens were cast monolithically. The shear strength test was summarized by flow chart in Figure 4-2. The designation 'NCS' indicates No confining strain or without confinement strain.

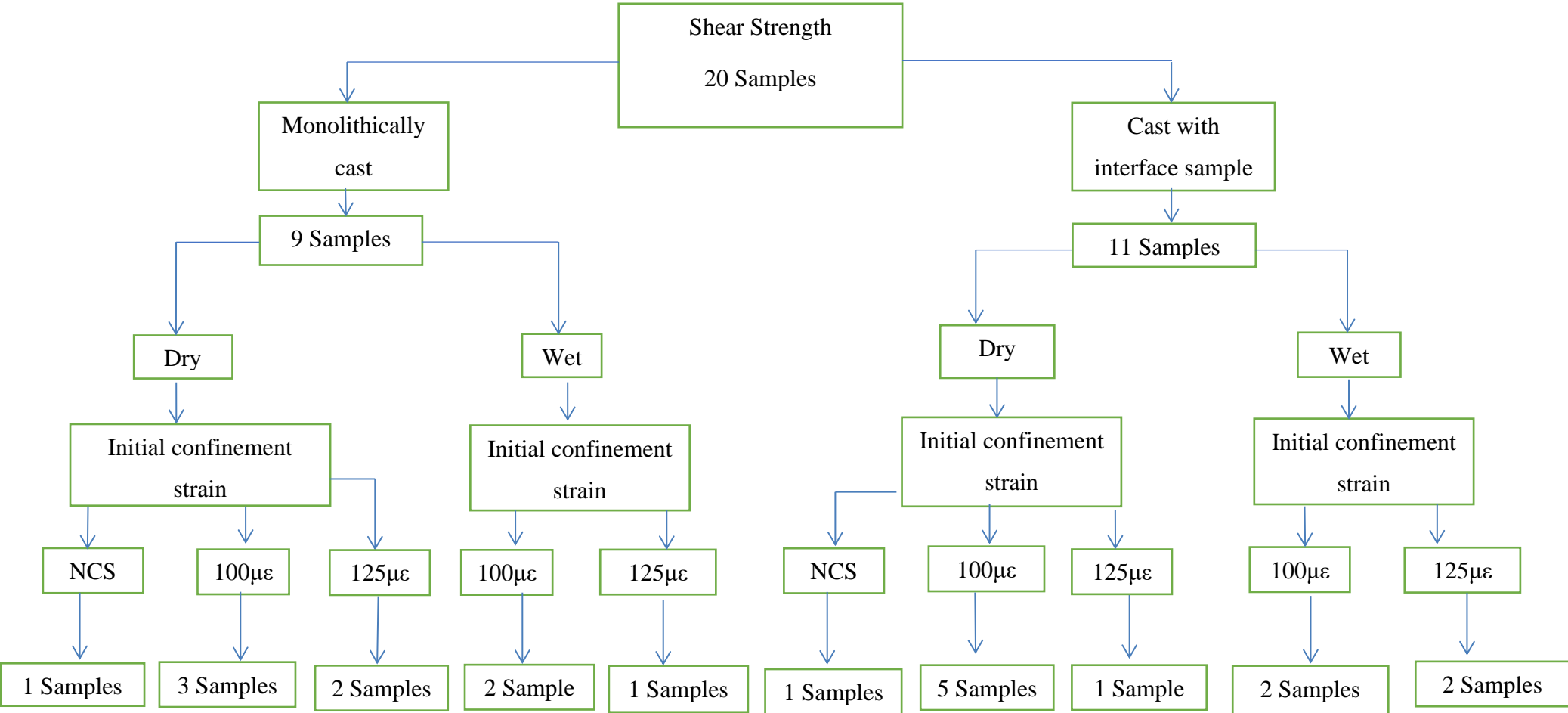


Figure 4-2: Flow chart of test program for shear samples.

The result from the experimental program was P (force) displayed in data logger. In order to convert the shear force to shear stress the force was divided by shear plane area. The failure shear stress was calculated by the following equation

$$\tau = \frac{P}{A} \dots\dots\dots\text{Equation 4-1}$$

Where: τ is shear strength in MPa, P is the maximum load carried by the specimen at failure in kN and A is the area of shear plane in mm². The shear area is the contact area of old and new concrete for shear strength. The length and width of the shear plane was 250mm and 125mm respectively.

4.1.1 Monolithically Cast Samples

Nine specimens without interface were tested with different confinement strain and environmental condition. For confinement variation, the initial strain on the confinement reinforced bar was taken as 125 $\mu\epsilon$ and 100 $\mu\epsilon$ and without confinement bar. For environmental condition, 3 samples were tested underwater and 6 samples were tested under dry environmental conditions.

For Specimen MSD-1, the sample tested monotonically failed at 197kN and the failure shear stress was 6.31MPa the initial confining strain was 125 $\mu\epsilon$. The failure was occurred at the notch of the specimen and the failure surface was rough due to the existence of aggregate at the interface. crack propagated around the aggregate when the surrounding paste was weaker than the aggregate, otherwise, the crack cut through the aggregate. The same failure mode was seen on all specimen and for initial confining strain 100 $\mu\epsilon$ and without confining strain, there are also the contribution of confinement. The specimens tested underwater shows similar deformation path but reduction in strength due to an increase in load, moreover the formation of micro-cracks is inevitable. The adsorbed water in the micro-cracks tends to impose a cleaving action due to the water pressure. This phenomenon promotes the crack propagation in the concrete leading to reduced stiffness and strength of concrete. The confinement of the confining bar was measured using a steel strain gauge. From this stress-confining strain was obtained as shown in Figure 4-3, Figure 4-4 and Figure 4-5.

From this graph shown below for sample MSD-2 the resistance of shear is by cohesive (adhesive and aggregate interlock) as shown in the figure as region A before debonding occur and at 4.2 MPa crack occurs and when more load is applied, the shear resistance is by friction between aggregate and external confinement bar as shown in the figure as region B after debonding occur.

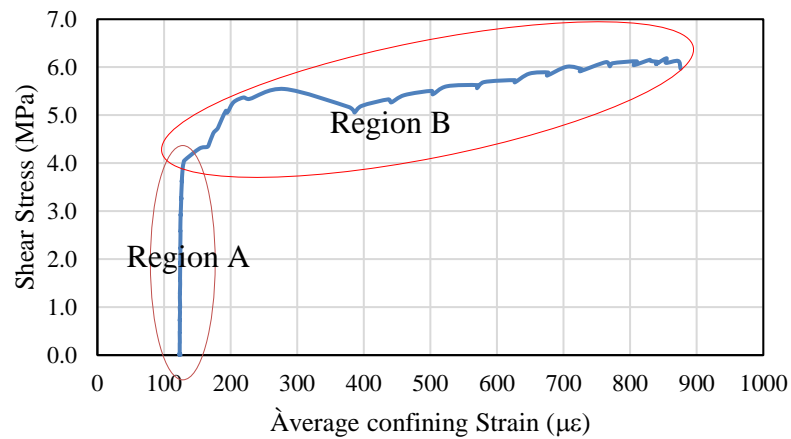


Figure 4-3: Stress-confining strain diagram of MSD-2 with 125 $\mu\epsilon$ initial confining strain.

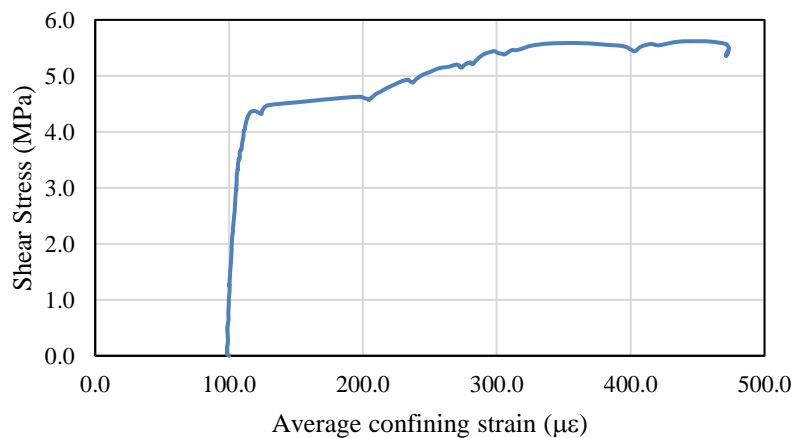


Figure 4-4: Stress-confining strain diagram for MSD-4 with 100 initial confining strain.

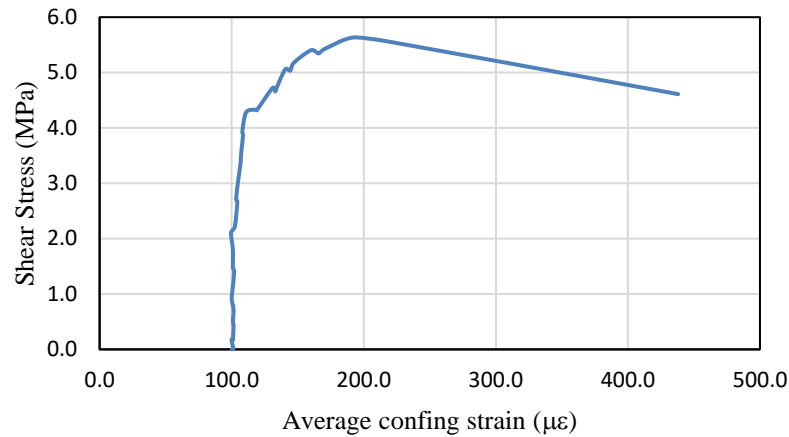


Figure 4-5: Stress-strain diagram for specimen MSD-5 with 100 $\mu\epsilon$ initial confinement strain.

4.1.2 Cast with Interface Sample

Eleven specimens with interface were tested, with different confinement strain and environmental condition. For confinement variation, the initial strain on the confinement reinforced bar was taken as 125 $\mu\epsilon$ and 100 $\mu\epsilon$ and without initial confinement strain. For environmental condition case, 4 samples were tested underwater and 7 samples were tested under dry environmental conditions.

For Specimen ISD-1 The sample tested monotonically failed at 120kN and the failure shear stress 2.53MPa. the failure occurred at the notch of the specimen. the failure surface was smooth due to the absence of aggregate at the interface. crack propagated around the paste when the surrounding paste was getting weaker than sample failed, the same failure mode was seen on all specimen cast with interface specimen and for initial confining strain 100 $\mu\epsilon$ and 150 $\mu\epsilon$ there are also the contribution of confinements. And Similar to monolithically cast sample the presence of water reduced stiffness and strength of concrete.

The confinement of the confining bar was measured using a steel strain gauge. From this stress-confining strain was obtained as shown in Figure 4-6 and Figure 4-7.

From this average confining strain-shear stress graph for sample BSD-2 the resistance of shear is by cohesive (adhesive and mechanical interlock) as shown in the Figure 4-6 as

region A, and at 2.5 MPa crack occurs and when applied more load the shear resistance is by friction between aggregate and external confinement bar as shown in the Figure 4-6 as region but for region B the contribution by friction between aggregate was very small.

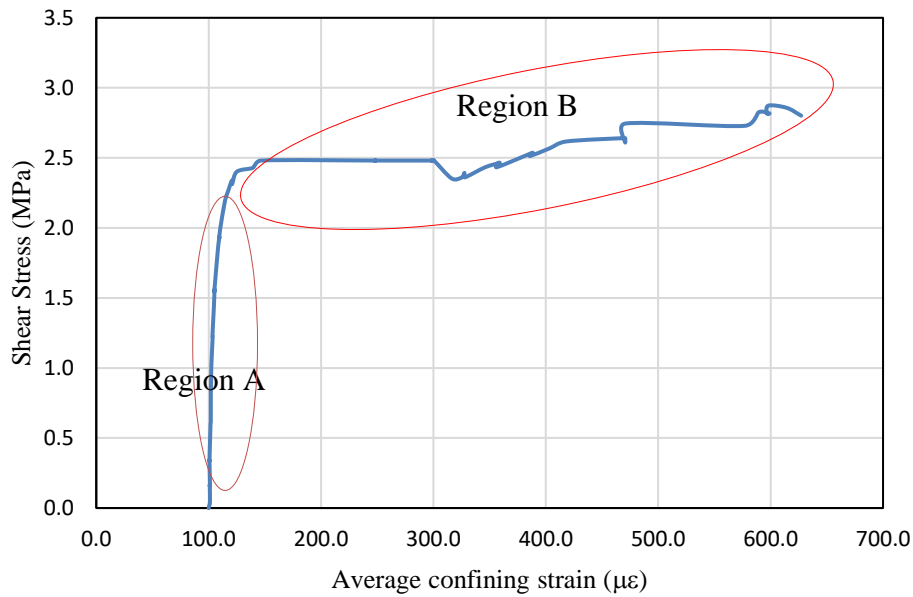


Figure 4-6: Shear stress-confinement strain diagram for ISD-2 with 100 initial confinement strain.

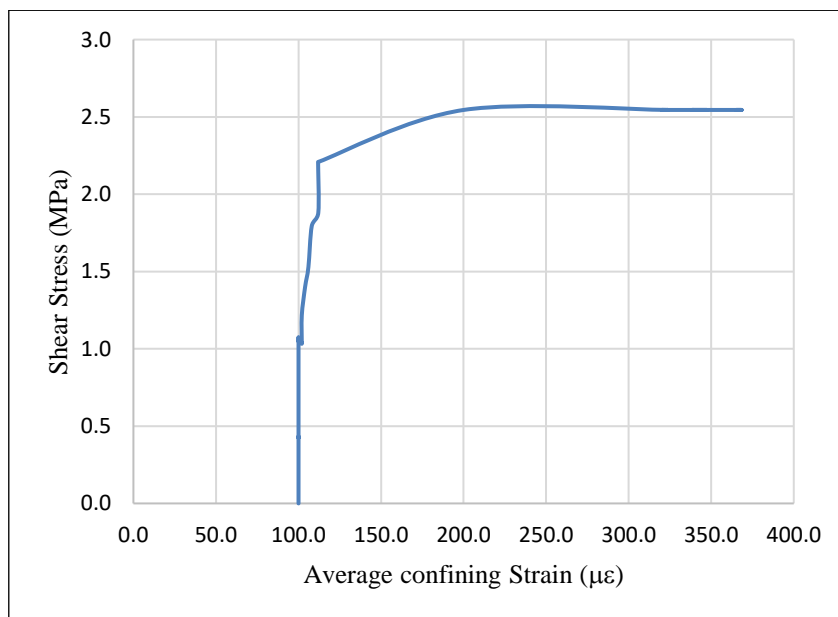


Figure 4-7: Shear stress-confinement strain diagram for ISD-4 with 100 initial confinement strain.

4.2 Discussion for Shear Strength Result

4.2.1 Comparison of Monolithically Cast and Cast with the Interface Samples at Monotonic Loading and Dry Environmental Condition.

1. Shear Strength for Monolithically Cast and Cast with Interface Specimens without Confinement Strain.

The shear strength for no confinement strain was summarized in Table 4-1. This is the pure shear capacity of concrete.

Table 4-1: Shear strength test result without external confining bar.

Monolithically Cast		Cast with Interface	
Designation	Dry (MPa)	Designation	Dry (MPa)
MSD-9	3.680	ISD-11	0.832

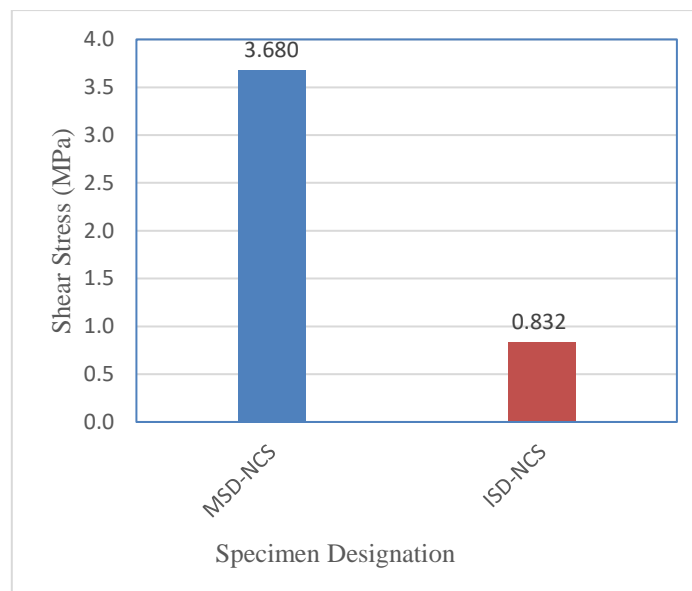


Figure 4-8: Chart of shear bond strength for samples without confining bar.

As it is presented in Figure 4-8, the existence of a Joint between substrate and overlay concrete at the interface significantly reduces the shear strength. A reduction in shear strength of up to 77.39 % was observed for dry condition specimens without confinement strain. From the above it was observed a great reduction in shear that is why great care must be taken for samples with interface and it is very big reduction in shear.

2. Shear Strength for Monolithically Cast and Cast with Interface Specimens with 100µε initial confining strain

The shear strength for 100 µε initial confinement strain was summarized in Table 4-2. The effect of water also shown in table. For specimens tested under wet environmental condition the specimens were left submerged in water before the test was commenced for about 24 hours, water is bound to enter some portions of the pores of the concrete and test at submerged water tanker.

Table 4-2: Shear strength test result in with 100µε initial confining strain.

Monolithically Cast Samples				Cast with Interface Samples			
Designation	Dry (MPa)	Designation	Wet (MPa)	Designation	Dry (MPa)	Designation	Wet (MPa)
MSD-3	5.856	MSW-7	5.154	ISD-2	2.873	ISW-9	2.649
MSD-4	5.634	MSW-8	5.098	ISD-3	2.705	ISW-10	2.137
MSD-5	5.442			ISD-4	2.545		
				ISD-5	2.439		
				ISD-6	2.400		
Average	5.644		5.126	Average	2.593		2.393

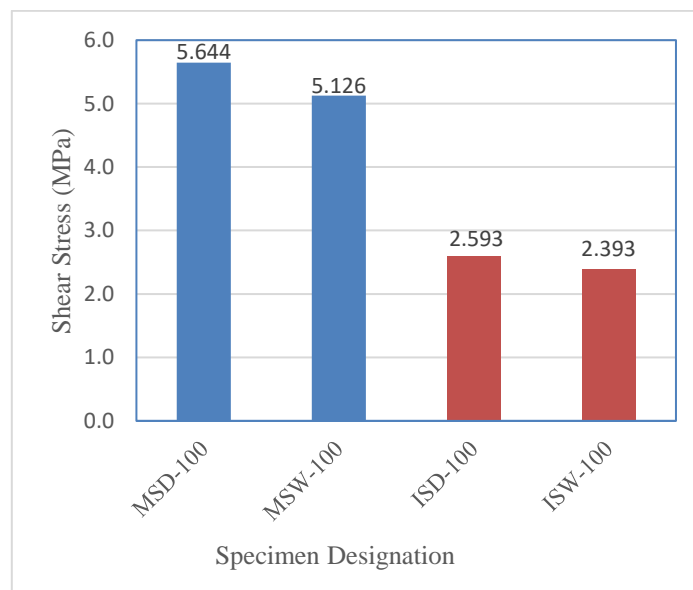


Figure 4-9: Chart of shear strength with 100µε initial confining strain.

As it is presented in Figure 4-9, the existence of a Joint between substrate and overlay concrete at the interface significantly reduces the shear strength. A reduction in shear strength of up to 54.07 % was observed for dry condition and 57.06% for the wet condition for 100 $\mu\epsilon$ initial confinement strain.

From this result it was observed the presence of water affect for both monolithically casted sample and cast with interface sample. The presence of water decreases 9.17% for monolithically caste sample 7.71% for cast with interface samples and have similar effect for both cases.

The reduction of shear was 77.39% for no confinement strain and it reduces to 54.07% for 100 $\mu\epsilon$, although due to confinement effect the gap was reduces it is still its significant reduction in shear strength.

3. Shear Strength for Monolithically Cast and Cast with Interface with 125 $\mu\epsilon$ Initial Confining Strain

The shear strength for 125 $\mu\epsilon$ initial confinement strain was summarized in Table 4-2. The effect of water also shown in table. For specimens tested under wet environmental condition the specimens were left submerged in water before the test was commenced for about 24 hours, water is bound to enter some portions of the pores of the concrete and test at submerged water tanker.

Table 4-3: Shear strength with 125 $\mu\epsilon$ Initial confining strain.

Monolithically Cast Samples				Cast with Interface Samples			
Designation	Dry (MPa)	Designation	Wet (MPa)	Designation	Dry (MPa)	Designation	Wet (MPa)
MSD-1	6.315	MSW-6	6.016	ISD-1	3.818	ISW-7	4.002
MSD-2	6.187					ISW-8	3.776
Average	6.251		6.016		3.818		3.889

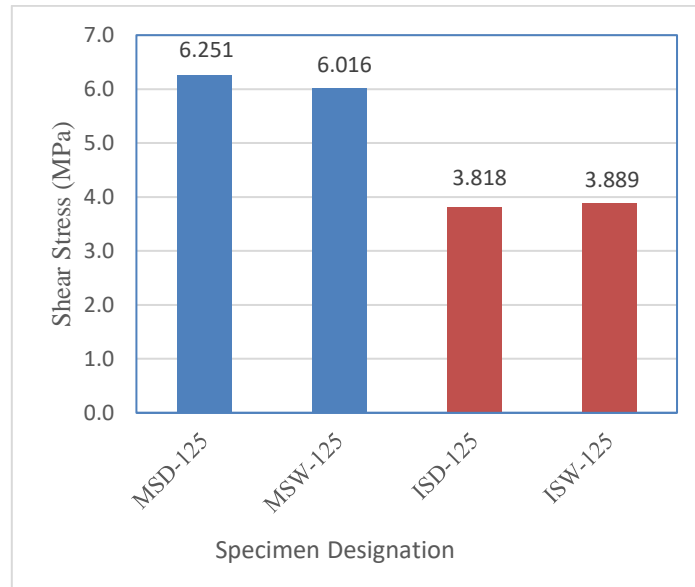


Figure 4-10: Chart of shear strength with 125 $\mu\epsilon$ initial confining strain.

As it is presented in Figure 4-10, the existence of a Joint between substrate and overlay concrete at the interface significantly reduces the shear strength. A reduction in shear strength of up to 38.92 % was observed for dry condition and 37.78 was observed for the wet condition at 125 $\mu\epsilon$ initial confinement strain.

From this result it was observed the presence of water affect for both monolithically casted sample and cast with interface sample. The presence of water decreases 3.75 % for monolithically caste sample -1.85 % for cast with interface samples and have similar effect for both cases this result for cast with interface was unexpected but after failed sample it was observed rougher surface for sample test at wet environmental condition.

The reduction of shear was 77.39% for no confinement strain and it reduces to 54.07% at 100 $\mu\epsilon$ and 38.92 % for 125 $\mu\epsilon$ initial confining strain. From this the contribution of confinement is larger for cast with interface sample than monolithically cast sample.

4. Shear Strength for Monolithically Cast with No Confinement, 100 and 125 Initial Confining Strain

The shear strength for monolithically casted sample with three initial confinement strain was observed. The initial confinement strain was no confinement strain, 100 $\mu\epsilon$ and 125 $\mu\epsilon$ initial confinement was summarized in Table 4-4.

Table 4-4: Shear strength for monolithically cast samples.

1.Initial confining strain 125				2.Initial confining strain 100				3.Without confinement	
Desig.	Dry (MPa)	Desig.	Wet (MPa)	Desig.	Dry (MPa)	Desig.	Wet (MPa)	Desig.	Dry (MPa)
MSD-1	6.315	MSW-6	6.016	MSD-3	5.856	MSW-7	5.154	MSD-	3.68
MSD-2	6.187			MSD-4	5.634	MSW-8	5.098		
				MSD-5	5.442				
Average	6.251		6.016	Average	5.644		5.126		3.680

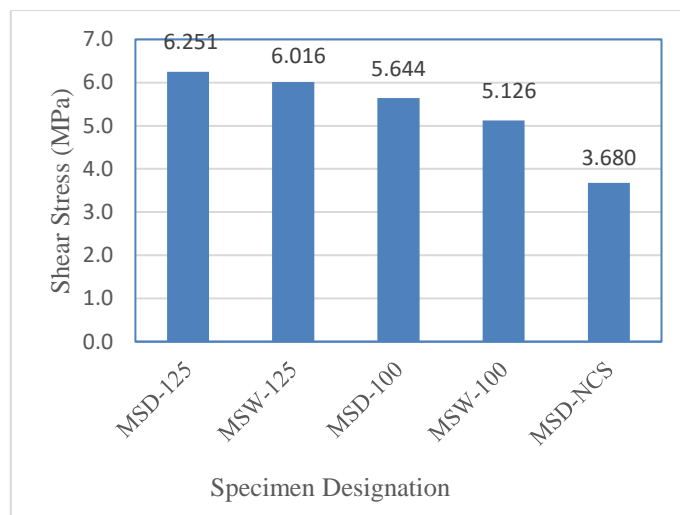


Figure 4-11: Chart of shear bond strength for monolithically cast sample.

As it is presented in Figure 4-11, for monolithically cast samples due to increasing confining strain from 0 to 100 $\mu\epsilon$ significantly increases the interface shear strength 53.37% .and increasing from 0 to 125 $\mu\epsilon$ increases the shear strength 69.84% and increasing from 100 to 125 increases 10.74%.For wet condition increasing initial confinement strain from 100 $\mu\epsilon$ to 125 $\mu\epsilon$ in 17.36%.From this experiment it was observed increasing initial confinement strain increases the interfacial shear strength for monolithically casted samples.

5. Shear Strength Cast with Interface with No Confinement, 100 and 125 Initial Confining Strain

The shear bond strength for cast with interface sample with three initial confinement strain was observed. The initial confinement strain was no confinement strain, 100 $\mu\epsilon$ and 125 $\mu\epsilon$ initial confinement was summarized in Table 4-4.

Table 4-5: Shear strength for cast with interface samples.

Initial confining strain 125 $\mu\epsilon$				Initial confining strain 100 $\mu\epsilon$				Without confinement	
Desig.	Dry (MPa)	Desig.	Wet (MPa)	Desig.	Dry (MPa)	Desig.	Wet (MPa)	Desig.	Dry (MPa)
ISD-1	3.818	ISW-7	4.002	ISD-2	2.873	ISW-9	2.649	ISD-11	0.832
		ISW-8	3.776	ISD-3	2.705	ISW-10	2.137		
				ISD-4	2.545				
				ISD-5	2.439				
				ISD-6	2.400				
Average	3.818		3.889		2.592		2.393		0.832

The Abbreviation ‘‘Desig.’’ Means Designation of samples.

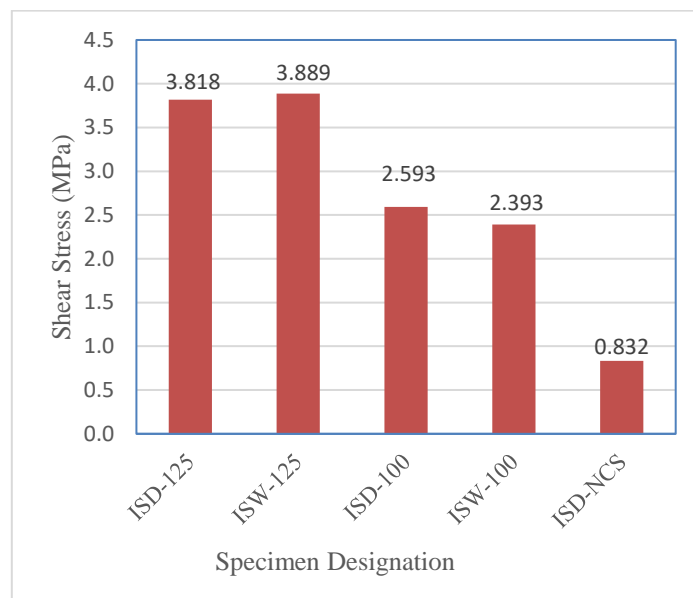


Figure 4-12: Chart of shear bond strength for cast with interface sample.

As it is presented in for cast with interface samples due to increasing confining strain from 0 (without confining bar) to 100 $\mu\epsilon$ significantly increases the interfacial shear strength 211.60 % ,and increasing from 0 to 125 $\mu\epsilon$ increases the shear strength 358.85 % and

increasing from $100\mu\epsilon$ to $125\mu\epsilon$ increases 47.25%. For wet condition increasing initial confinement strain from $100\mu\epsilon$ to $125\mu\epsilon$ in 62.50%. From this experiment it was observed increasing initial confinement strain increases the interfacial shear strength for cast with interface sample. Comparing with monolithically cast sample the contribution of confinement has larger effect.

4.2.2 Comparison of Monolithically Cast and Cast with Interface Sample

The effect of initial confinement strain on interfacial shear strength was summarized in Figure 4-13. From the graph as the initial confinement strain increase the shear strength also increase. The presence of water also reduces shear strength up to 10%. For the cast with interface samples, at $125\mu\epsilon$ initial confinement tested at wet condition had slightly higher shear strength than dry shear strength. This was unexpected but after test of sample it was observed rougher surface for sample test at wet environmental condition than dry environmental condition.

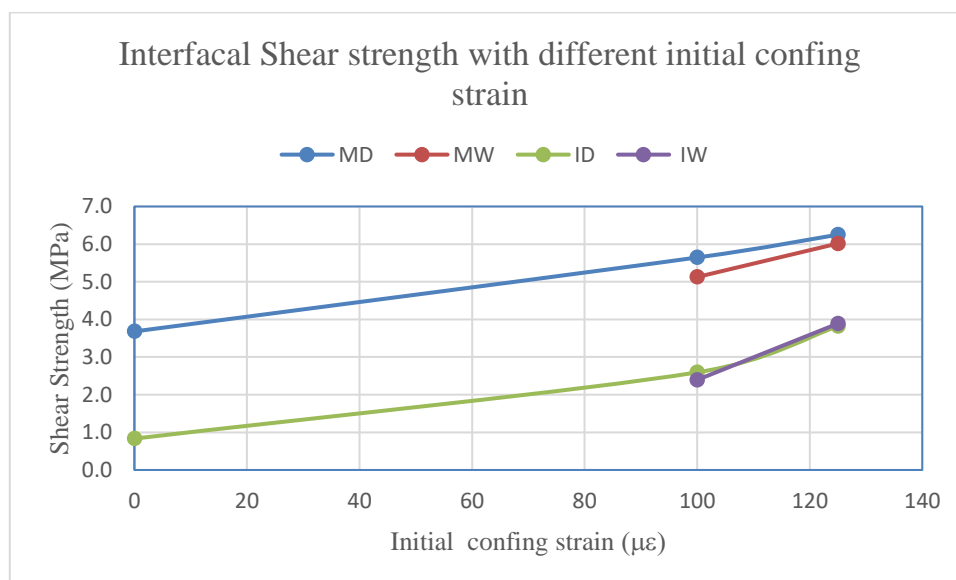


Figure 4-13: Summary of interfacial shear strength.

4.3 Summary of the Experimental Program for Shear

The results of the experiment for monolithically cast samples are summarized in Table 4-6. For sample MSD-9, the designation “NCB” means the sample was tested without confinement bar and no confinement strain was measured. This indicates the capacity of concrete is adhesion and friction, without external confinement bar.

Table 4-6: Summary of results for monolithically cast samples.

Specimen Designation	Environmental Condition	Weight (kg)	concrete (MPa)	Failure Load (kN)	Failure Stress (MPa)	Initial Confining Strain ($\mu\epsilon$)	Max Average Confining Strain ($\mu\epsilon$)
MSD-1	Dry	42.365	41.57	197.33	6.315	125	890.235
MSD-2	Dry	43.130	44.23	193.33	6.187	125	875.715
MSD-3	Dry	43.350	38.97	183.00	5.856	100	840.475
MSD-4	Dry	43.120	37.76	176.07	5.634	100	473.334
MSD-5	Dry	42.375	36.92	170.07	5.442	100	468.570
MSW-6	Wet	42.300	38.03	188.00	6.016	125	643.967
MSW-7	Wet	41.870	39.23	161.06	5.154	100	638.095
MSW-8	Wet	42.500	41.82	159.31	5.098	100	467.620
MSD-9	Dry	42.165	36.16	115.00	3.680	NCB	NCB

The results of the experiment for cast with the interface are summarized in Table 4-7. For sample ISD-11, the designation “NCB” means the sample was tested without confinement bar and no confinement strain was measured.

Table 4-7: Summary of Results of Cast with interface samples.

Specimen Designation	Environmental Condition	Weight (kg)	Substrata concrete (MPa)	overlay concrete (MPa)	Failure Load (kN)	Failure Stress (MPa)	Initial Confining Strain ($\mu\epsilon$)	Max Average Confining Strain ($\mu\epsilon$)
ISD-1	Dry	43.025	43.077	29.525	119.30	3.818	125.00	650.253
ISD-2	Dry	42.700	35.968	33.333	89.79	2.873	100.00	632.143
ISD-3	Dry	43.525	45.144	29.033	84.53	2.705	100.00	391.620
ISD-4	Dry	42.375	41.492	29.82	79.53	2.545	100.00	381.380
ISD-5	Dry	43.150	39.682	35.44	76.23	2.439	100.00	205.480
ISD-6	Dry	43.025	33.045	29.983	75.00	2.400	100.00	387.860
ISW-7	Wet	42.125	32.922	34.24	125.05	4.002	125.00	343.098
ISW-8	Wet	42.795	35.993	31.284	118.05	3.778	125.00	538.543
ISW-9	Wet	43.065	34.158	38.295	82.78	2.649	100.00	343.098
ISW-10	Wet	42.150	34.824	29.308	66.78	2.137	100.00	409.520
ISD-11	Dry	42.700	33.20	36.82	26.00	0.832	NCB	NCB

4.4 Observation for Push off Test



Figure 4-14: Crack pattern of the shear test.



Figure 4-15: The Failed surface of monolithically cast and cast with interface sample.

Shear strength of concrete was significantly reduced due to the presence of an interface. For cast with interface sample, the adhesive is small. And the surface of the fail's specimen is smooth for cast with interface sample the adhesive is strong and crates rough surface. Failure occurs at the interface because it is a weak zone.

4.5 Direct Tensile Test

A direct tensile strength test of concrete was carried using a newly prepared set up. As concrete is weak in tension, the addition of interface between old and new concrete further reduces the tensile strength and hence the specimen gets much weaker in tension and the tensile stress is mainly contributed to adhesion.

The new frame was built and the specimen was tested by using center hole jack for applying tensile load. The shape of samples is shown in Figure 4-16 and the support condition was fixed at the bottom and tensile force was applied at the top using center hole jack and strain was measured using a strain gauge.

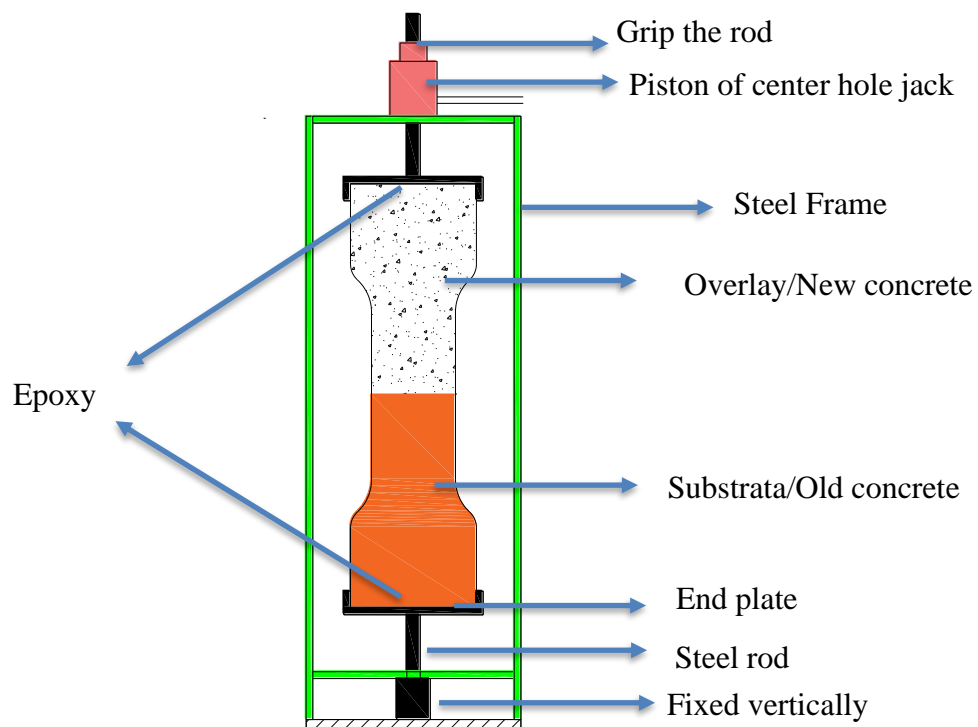


Figure 4-16: Dog bone mold

4.5.1 Result of the Cast with Interface Sample at the Dry Condition with Monotonic Tensile Loading

Three specimens for cast with interface samples were tested by a direct tensile test. Load at dry concrete strain gauge was attached to concrete to obtain stress-strain curve from the direct tensile test of sample BTD-2 that is presented in Figure 4-17. the tensile capacity and max slip observed were summarized in Table 4-8.

Table 4-8: Result of cast with interface sample tested at dry condition.

Composition	Max load (kN)	Max tensile stress (MPa)
ITD-1	9.45	0.631
ITD-2	10.83	0.722
ITD-3	9.82	0.655

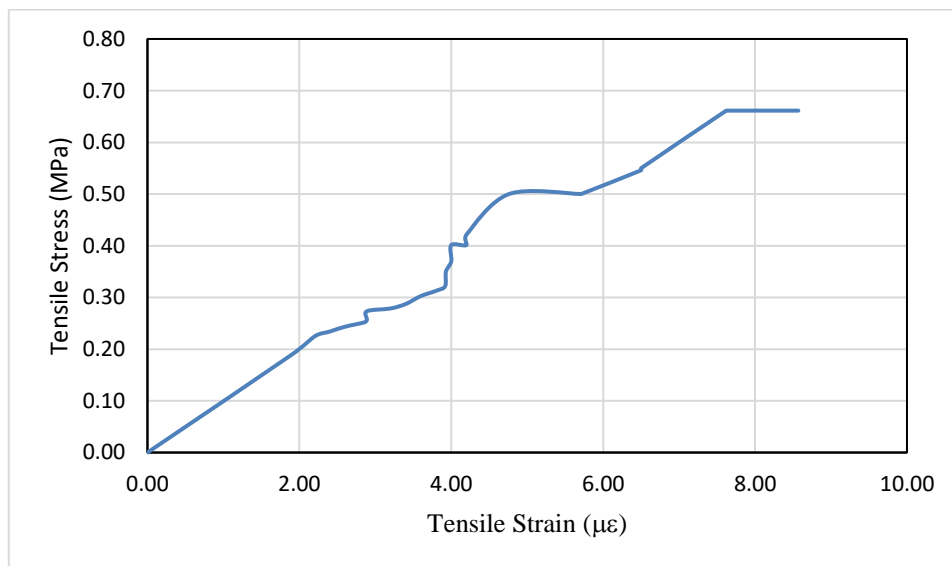


Figure 4-17: Tensile stress -tensile stain for sample BTD-2

4.5.2 Result of the Monolithically Cast Sample at the Dry Condition with Monotonic Tensile Loading

Six specimens for monolithically cast specimen were cast with cylindrical sample and were tested by splitting tensile load at the dry environmental condition. The splitting tensile strength calculated using the following equation. The result was summarized in **Error! Reference source not found.**

$$\sigma = \frac{2P}{\pi A} \dots\dots\dots \text{Equation 4-2}$$

Where: σ is splitting tensile strength in MPa, P is the maximum load carried by the composite specimen at failure in N and A is the area of Interface plane (shear plane) in mm^2 .

Table 4-9: Splitting tensile test result.

Composition	Splitting tensile strength (MPa)
MTD-1	3.856
MTD-2	3.065
MTD-3	3.839
MTD-4	3.956
MTD-5	3.579
MTD-6	3.752

4.6 Discussion for The Tensile Result

Since the samples for the monolithically casted test was using splitting tensile test, and for cast with interface sample, they were tested direct tensile test it not realistic to compare both cases directly. From the literature indicates splitting tensile strength gives larger results than the direct tensile test. to convert the splitting tensile strength result to a direct tensile test result numerical equation was used. The tensile strength of concrete is proportional to the square root of compressive strength. Equation 4-2 and Equation 4-3 are based on (Chhorn, Hong, & Lee, 2018) and Equation 4-4 based on (Ros & Shima, 2013).

In order to take the size effect into account, the conversion from the cube sample (150x150x150) to the standard cylindrical sample (ϕ 150x300) cylinder/cube conversion factor (K_f) is taken as 0.8. Hence, the corresponding compressive strength values for the cylinder samples are attained by using the compressive strengths obtained from the cube samples. Compressive strengths were converted.

$$0.8f_{cu,150 \times 150 (cube)} = f_{c,\phi 150 \times 300 (cylinder)} \dots \dots \dots \text{Equation 4-3}$$

Direct tensile strength: $f_{ct} = 0.26 - 0.42\sqrt{f_c}$ **Equation 4-4**

Split tensile strength1: $f_{sp} = 0.5\sqrt{f_c}$ **Equation 4-5**

Flexural tensile strength: $f_r = 0.68f_{cu}^{0.5}$ **Equation 4-6**

Where:

f_{cu} = Specified compressive strength of standard concrete cylinder 150x150x150mm.

f_c = Specified compressive strength of standard concrete cylinder 150dia x30mm.

f_{sp} = Splitting tensile strength of standard concrete cylinder 150dia x30mm.

f_r = flexural tensile strength of standard concrete prism 500x100x100mm.

Many types of research provide formula in the relation between compressive strength and tensile strength. (Ghaffar, Chaudhry, & Kamran, 2015) and (Ghaffar et al., 2015) So, for monolithically cast samples the cubic compressive strength result and splitting tensile result was converted to concrete direct tensile capacity. From upper data, it was obtained upper and lower boundary for direct tensile strength.

Equation 4-7: Experimental splitting tensile tests and predict tensile strength based on proposed formulas.

ID	Cubic compressive strength (MPa)*	Splitting tensile strength (MPa)*	cylinder compressive strength (MPa)***	Direct tensile strength 1(MPa)***	Direct tensile strength 2(MPa)***
MTD-1	39.490	3.811	33.567	1.461	2.361
MTD-2	33.593	3.283	28.554	1.348	2.177
MTD-3	37.147	3.899	31.575	1.417	2.290
MTD-4	33.650	3.456	28.603	1.349	2.179
MTD-5	33.283	3.284	28.291	1.342	2.167
MTD-6	38.195	3.612	32.466	1.437	2.322

Where: * is results obtained from the experimental program and *** is predicted results using previous studies.

Direct tensile strength1: $f_{ct} = 0.26\sqrt{f_c}$ and Direct tensile strength2: $f_{ct} = 0.42\sqrt{f_c}$

4.6.1 Comparison of Monolithically Cast and Cast with Interface at Monotonic Tensile Loading Under Dry Condition

The tensile strength for the monolithically cast sample and for cast with the interface was summarized in Table 4-10. Tensile strength 1 is the lower limit of direct tensile teste and Tensile strength 2 is the upper limit of direct tensile strength.

Table 4-10: Summary of result for the tensile test.

Monolithically cast samples	Tensile Strength 1 (MPa)	Tensile Strength 2 (MPa)	Cast with Interface sample	Tensile strength (MPa) Cast with in
MTD-1	1.461	2.361	ITD-1	0.630
MTD-2	1.348	2.177	ITD-2	0.720
MTD-3	1.417	2.290	ITD-3	0.655
MTD-4	1.349	2.179		
MTD-5	1.342	2.167		
MTD-6	1.437	2.322		
Average	1.392	2.249	Average	0.67

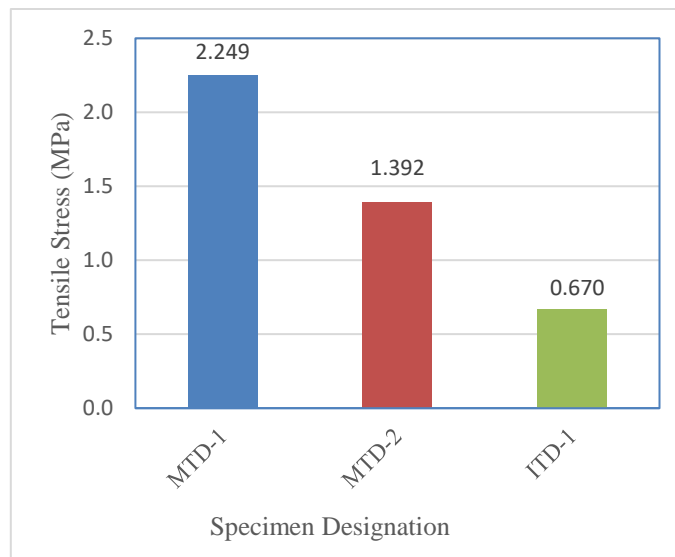


Figure 4-18: Tensile Strength test results.

As it is presented in Figure 4-18, the existence of a joint between substrate and overlay concrete at the interface significantly reduces the tensile strength. A reduction in tensile strength of up to 50 % to 70% was observed for the dry condition. But a solid conclusion could not be made due to the limited number of specimens tested.

4.6.2 Observation of Direct Tensile Test

After the test, crack patterns were located at the interface of old and new concrete.

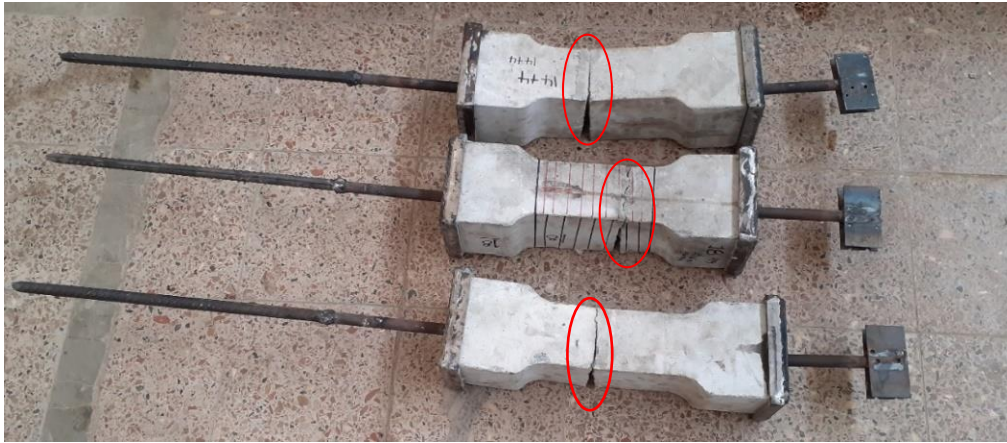


Figure 4-19: Crack pattern of failed samples.



Figure 4-20: Failed surface for cast with interface sample and tensile area of 150 mm length and 100mm width.



Figure 4-21: The Failed surface of Monolithically caste sample splitting tensile strength are 300mm length and 150 mm width.

As the specimen was being loaded cracks started propagating along with the interface and as the load being applied increased the crack opening width was also increased. Furthermore, the load caused complete detachment of concrete in the interface area. The direct tensile strength of concrete was significantly reduced due to the presence of an interface. For cast with interface sample, the adhesion was small.

4.7 Surface Roughness Evaluation

To evaluate the surface roughness, the surface of the sample were mapped by the handmade profile meter. Five sample profiles were mapped using profilometry. Three samples were monolithically cast and two samples were cast with the interface as shown in Figure 4-22 and Figure 4-23 measured at the center.

A two-dimensional profile for shear specimen, length of the rough r sample is 225mm and varying elevation. the shear area of the specimen was 250mm (X direction) length and 125mm (Y direction) width. By taking the center of Y or 62.5 then by varying X from 0 to 225 mm data was collected every 5 mm of X direction (total 46 data points) the shear area is shown in Figure 4-22 and Figure 4-23.

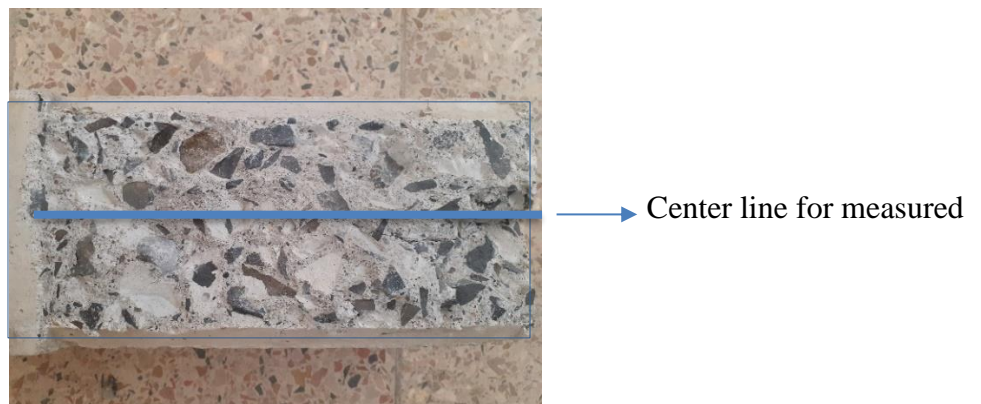


Figure 4-22: Shear area for monolithically cast cracked sample.



Figure 4-23: Shear area for cast with interface cracked sample.

4.7.1 Surface Roughness Parameters and Formulas

The main parameters in calculation roughness are R_p , R_v , Z' and R_a .

1. **Peak value (R_p)**

Highest peak. The maximum distance between the mean line and the highest point within the sample. It is the maximum data point height above the mean line through the entire data set.

2. **Vally value (R_v)**

Lowest valley. the maximum distance between the mean line and the lowest point within the sample. It is the maximum data point height below the mean line through the entire data set.

3. **Arithmetic Mean Roughness Profile (Z')**

The mean line is the average distance between the point within the sample. The mean line is laid on a cartesian coordinate system or midline.

$$Mean = z' = \frac{z_1 + z_2 + z_3 + z_4 + \dots + z_n}{n} \dots\dots\dots \text{Equation 4-8}$$

4. **Arithmetic Mean Deviation of Roughness Profile (R_a)**

A section of standard length is sampled from the mean line on the roughness chart. The mean line is laid on a Cartesian coordinate system wherein the mean line runs in the direction of the x-axis and magnification is the y-axis. The value obtained with the formula on the right is expressed in millimeters (mm) when $y=f(x)$.

$$R_a = \frac{|z_1 - z'| + |z_2 - z'| + |z_3 - z'| + |z_4 - z'| + \dots + |z_n - z'|}{n} \dots\dots\dots \text{Equation 4-9}$$

4.7.2 Mapping Surface Profile

The following points were obtained from the experiment:

Table 4-11: Elevation points.

		ISW-9	ISD-3	MSW-9	MSD-2	MSD-1
#	X (mm)	Z (mm)	Z (mm)	Z (mm)	Z (mm)	Z (mm)
1	0	-0.92	0.61	-0.98	7.72	-4.37
2	5	-1.14	0.96	-0.38	5.10	-5.41
3	10	-1.14	1.07	0.01	2.20	-6.78
4	15	-0.83	1.64	-2.18	-0.70	-5.58
5	20	-0.70	0.05	-2.14	-0.91	-5.40
6	25	-0.63	0.15	-2.12	-0.67	-4.44
7	30	-0.50	-0.74	-2.94	0.39	-5.48
8	35	-0.25	-0.06	-3.43	-0.13	-6.10
9	40	-0.34	-0.10	-2.90	2.19	-4.68
10	45	0.13	1.18	-2.38	4.21	-2.52
11	50	0.42	1.36	-0.72	5.99	-0.68
12	55	0.01	1.35	0.20	6.46	0.93
13	60	0.13	0.15	0.48	6.13	-0.03
14	65	0.20	0.26	-0.37	4.14	1.63
15	70	-0.19	-0.53	1.30	3.03	1.27
16	75	-0.50	-0.26	1.28	3.73	1.67
17	80	-0.50	0.20	0.61	3.12	2.72
18	85	-0.65	-0.34	0.82	0.28	3.15
19	90	-0.11	-0.46	1.33	-0.98	4.25
20	95	0.00	-0.86	2.90	-1.44	2.26
21	100	0.18	-1.72	5.09	-1.74	0.74
22	105	0.31	-0.91	5.75	-2.60	2.09
23	110	0.01	-1.35	4.90	-2.51	3.00
24	115	-0.37	-1.13	4.61	-2.60	3.14
25	120	-0.09	-0.80	1.55	-2.61	3.23
26	125	0.14	1.25	0.42	-2.62	4.25
27	130	0.46	0.92	0.11	-2.61	5.30
28	135	0.74	-0.03	0.87	-2.60	6.00
29	140	0.96	-0.57	0.63	-1.47	6.18
30	145	1.08	0.18	0.76	0.38	5.73
31	150	1.13	0.70	4.40	0.35	5.69
32	155	1.02	0.39	3.09	-0.27	6.03
33	160	1.02	0.94	1.04	-2.61	6.68
34	165	1.03	0.41	0.85	-7.61	2.34
35	170	0.38	-0.45	-0.57	-5.61	2.50
36	175	-0.04	0.04	-1.50	-4.61	2.91
37	180	0.28	-0.35	-1.98	-2.61	3.57

38	185	0.16	-0.72	-1.58	-1.63	2.65
39	190	-0.81	0.12	-0.75	0.10	-1.12
40	195	-0.72	-0.15	-2.23	1.85	-5.73
41	200	-0.72	-0.32	-2.11	0.40	-5.73
42	205	-0.70	0.18	-2.11	1.03	-5.11
43	210	-0.58	0.33	-2.36	0.40	-4.76
44	215	0.67	-0.32	-2.83	-1.61	-5.45
45	220	0.81	-1.13	-2.67	-3.61	-4.82
46	225	1.09	-1.13	-1.80	-2.62	-5.85
R_a		0.539	0.628	1.870	2.570	3.912

4.7.2.1 Mapping Surface Profile for Monolithically Sample

Three failed (cracked) sample profiles were mapped using profilometry. For monolithically cast specimens it is rough surface due to the presence of aggregate at the interface. This gives larger mean roughness value as shown in Figure 4-24, Figure 4-25 and Figure 4-26.

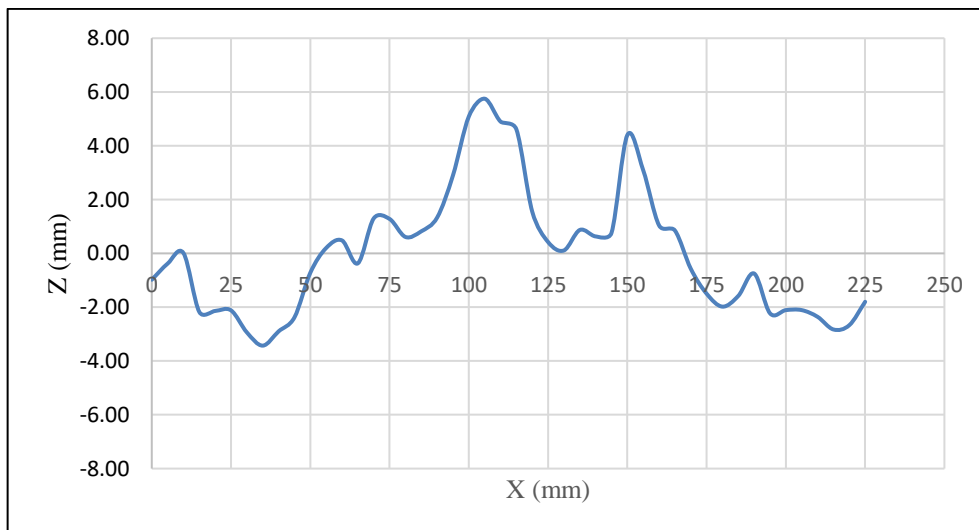


Figure 4-24: Roughness profile of specimen MSD-9.

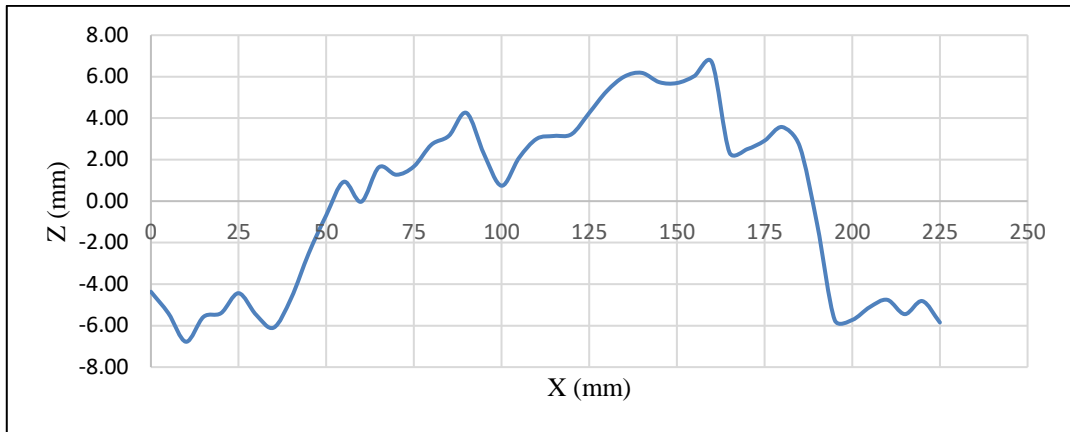


Figure 4-25: Roughness profile of specimen MSD-1.

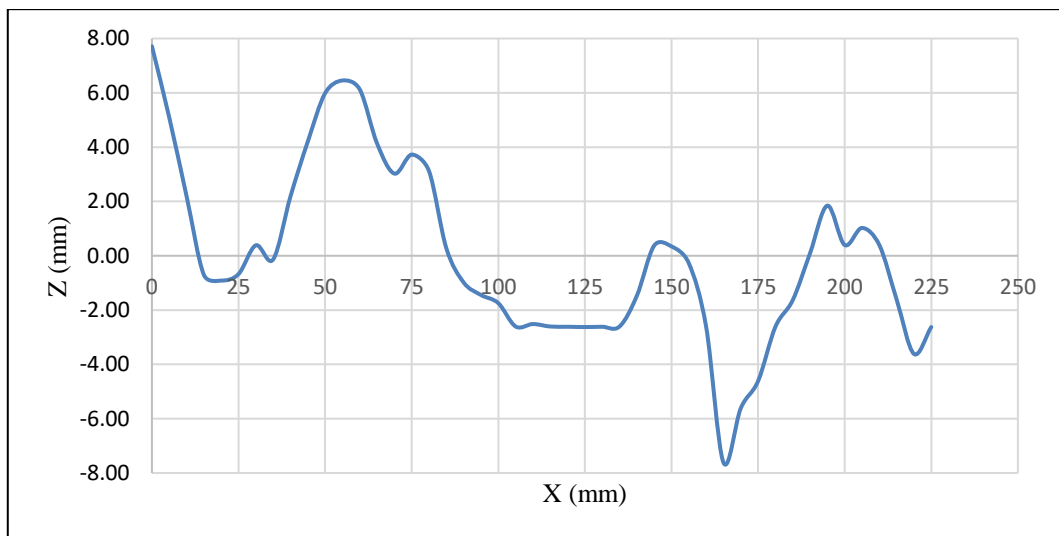


Figure 4-26: Roughness profile of specimen MSD-2.

4.7.2.2 Mapping Surface Profile for Cast with Interface Sample

Two Failed sample profiles were mapped using profilometry. For cast with interface specimen, it is a smooth surface due to the absence of aggregate and only pastes at the interface. This gives smaller value as shown in Figure 4-27 and Figure 4-28.

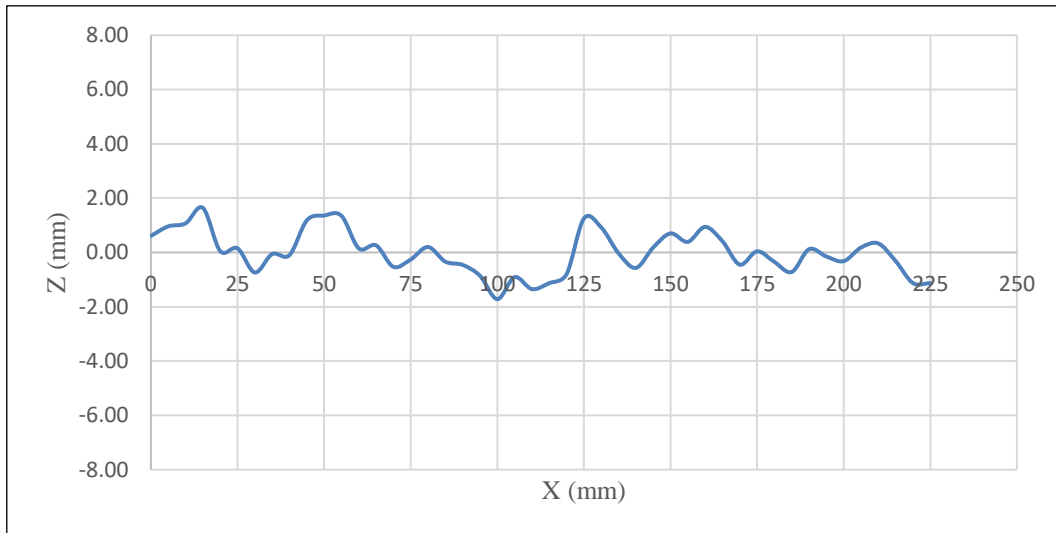


Figure 4-27: roughness profile of specimen ISD-3.

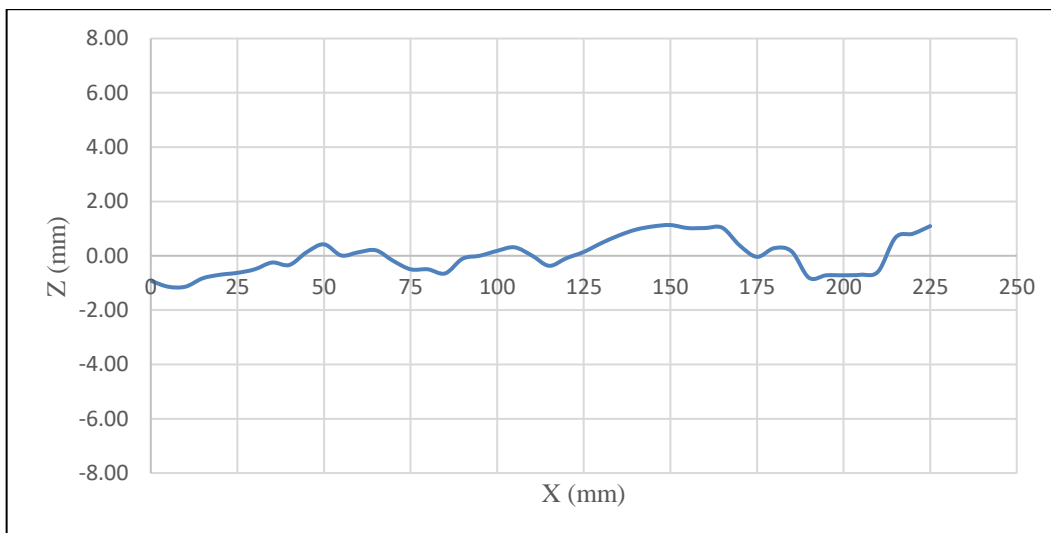


Figure 4-28: Roughness profile of specimen ISD-9.

4.7.2.3 Comparison of Mapped Surface Profile

Finally, the roughness of concrete with an interface and without interface are compared. From roughness profile existence of roughness increase shear strength between old and new concrete. For the two samples with the interface, the average roughness depth is smaller than for the three samples without interface Figure 4-29.

Table 4-12: Mean roughness and shear stress.

#	Designation	Initial confining strain ($\mu\epsilon$)	Mean depth (mm)	Mean roughness, Ra (mm)	Failure shear stress (MPa)
1	ISW-9	100	-2.71	0.539	2.65
2	ISD-3	100	4.71	0.628	2.70
3	MSW-7	100	-2.55	1.870	5.10
4	MSD-2	125	10.42	2.570	5.86
5	MSD-1	125	-7.88	3.912	6.31

From the graph shown in Figure 4-29, the arithmetical mean deviation of the profile, Ra coefficient, is a representative parameter and related to the shear strength particularly in shear strength. as Ra increases shear strength was also increases.

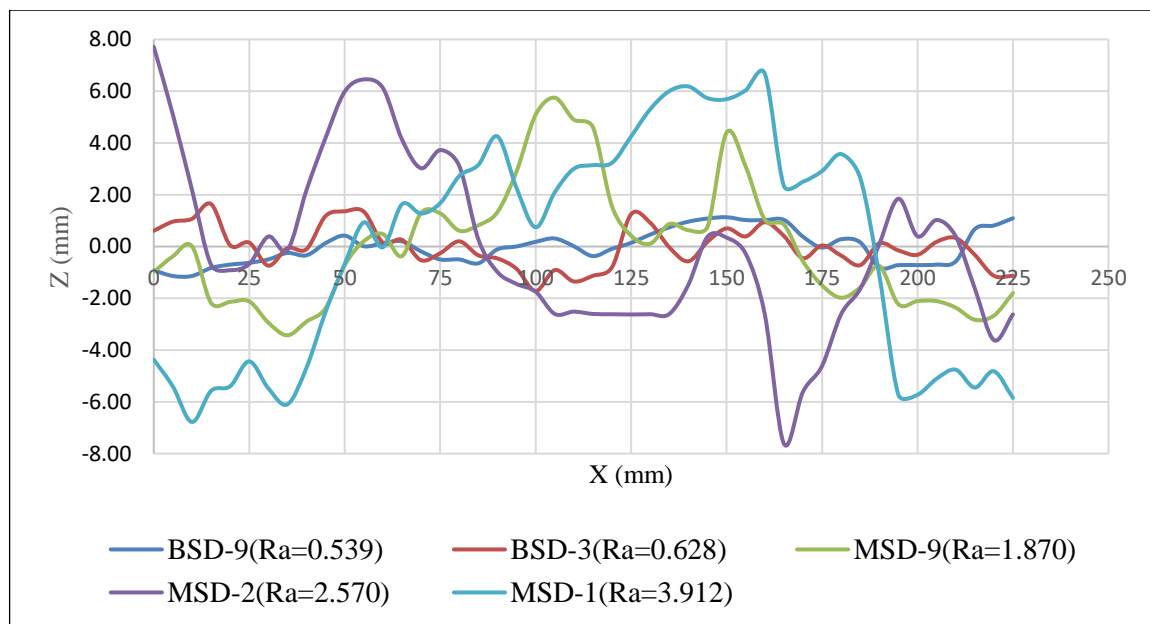


Figure 4-29: Ra off monolithically cast and cast with interface specimens.

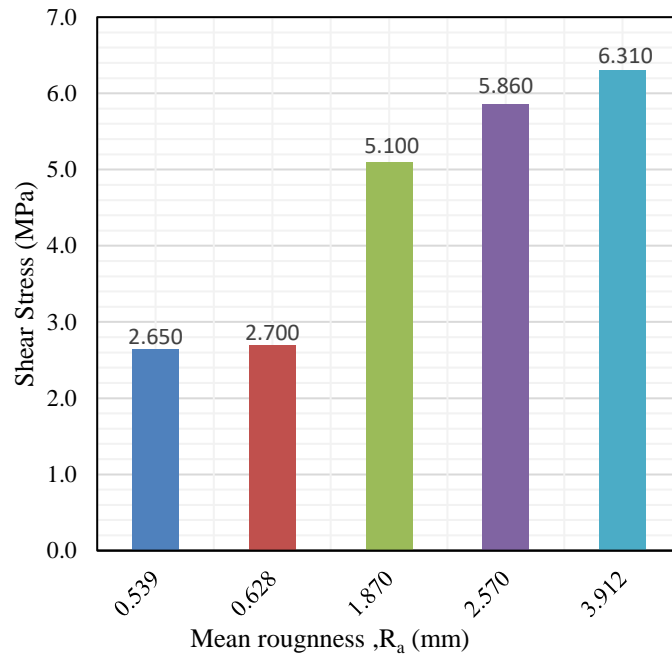


Figure 4-30: Mean roughness-shear stress for interface shear strength.

As it is presented in Figure 4-30, as the mean roughness increases (R_a) the shear strength also increases. For a rough interface, the friction between old and new concrete was mobilized significantly before the failure of the interface. On the other hand, for a very smooth interface, slipping movement is dominant than splitting so the contribution of friction action becomes small.

CHAPTER 5 FINITE ELEMENT MODELING

5.1 The Finite Element Modeling Tool

The analytical simulation of the push-off specimen for the shear test was done on a non-linear finite element software called DuCOM-COM3. This program was developed at the University of Tokyo. The simulation tool is primarily based on the study done in the Tokyo university laboratory during the past few years on the physical mechanisms of hydration, microstructure development and moisture transport coupled together in real-time. The program is an integral of the two simulation tools, DuCOM and COM3. DuCOM stands for Durability Models of Concrete and traces the development of concrete hardening (hydration), structure formation and several associated phenomena, from casting of concrete to a period of several months or even years while COM3 is a three-dimensional finite element simulating tool (Maekawa, Ishida, Chijiwa, & Fujiyama, 2012).

The program is capable of capturing the behavior of structures incorporating the effect of ingredient materials and environmental conditions. The platform has been proven to give results that fairly agree with experimental outputs in numerous researches.

5.2 Specimen Modeled for Specimens

A push-off specimen without an interface was modeled along with the confining bars. At this stage, monotonic loading condition and dry environmental condition was considered because for the sample with interface properties of the bond element needs more research.

5.3 Modeling the Specimens

5.3.1 Concrete

A mean value of compressive strength was taken from the cube tests conducted. The modulus of elasticity and tensile strength were obtained from Eurocode 2 corresponding to the obtained compressive strength.

Table 5-1: Properties of concrete used in the model

Concrete properties	Values
Initial stiffness	31 <i>GPa</i>
Cylindrical compressive strength	30 <i>MPa</i>
Tensile strength	3.5 <i>MPa</i>
Poisson's ratio	0.2

5.3.2 Reinforcement

The reinforcement layout for the internal bars is shown in Figure 5-1. It is simulated as smeared reinforcement by providing the reinforcement ratio in the concrete element. The reinforcement does not have any effect on the behavior of the interface aside from preventing failure at the top and sides of the concrete parts.

Properties	Internal bar (dia. 14)	Internal bar (dia 10)	External Bars (dia. 16)
Initial Stiffness	210 GPa	210 GPa	210 GPa
Yield Strength	304 MPa	511 MPa	544 MPa
Ultimate Strength	420 MPa	611 MPa	638 MPa

5.3.3 Support Condition

For shear sample model the nodes at the bottom of the push-off specimen were pinned allowing rotation about the support. The nodes at the top were also pinned and a downward vertical displacement was applied.

5.4 Modeling of Specimen for Shear Samples and tensile specimens

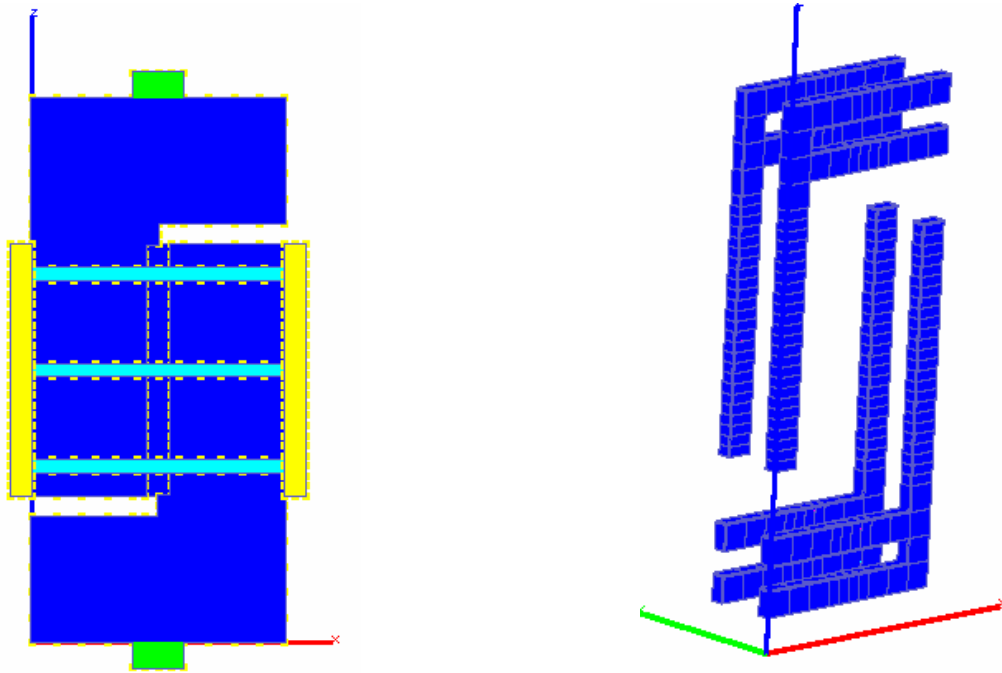


Figure 5-1: Side View and internal reinforcement for shear capacity test.

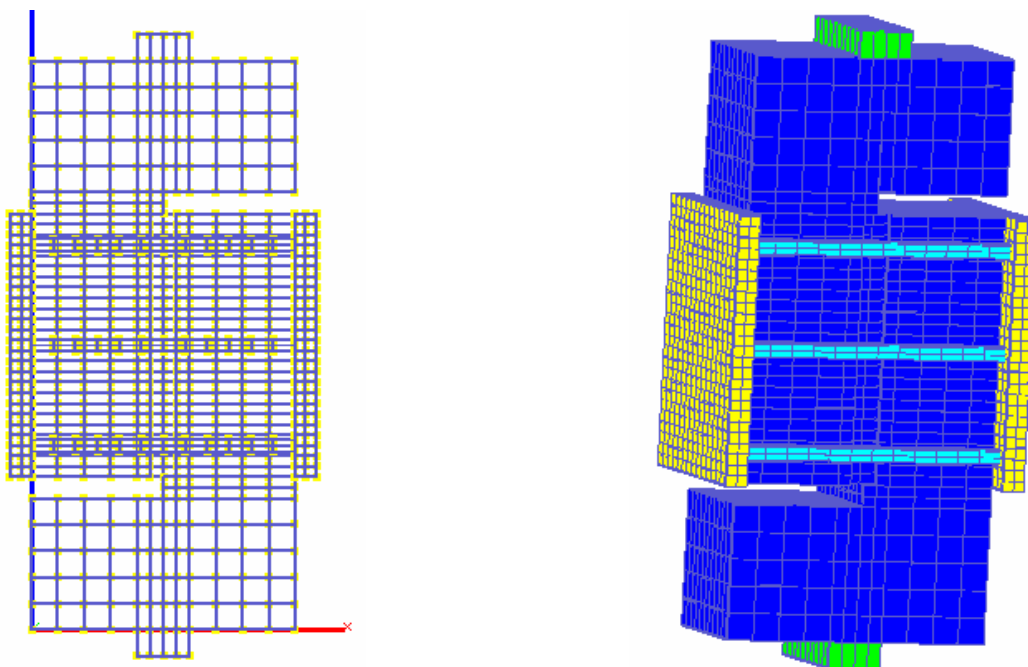


Figure 5-2: Meshing and 3d drawing of push-off shear test.

5.5 Result of Model for Elements

At this stage, only monotonic loading and dry conditions are considered since a strong model to capture the behavior of interfacial bond properties and water in the concrete is still fundamental. It needs more research on the bond properties concrete and presence of water.

5.5.1 Monolithically Cast Element by Monolithic Loading

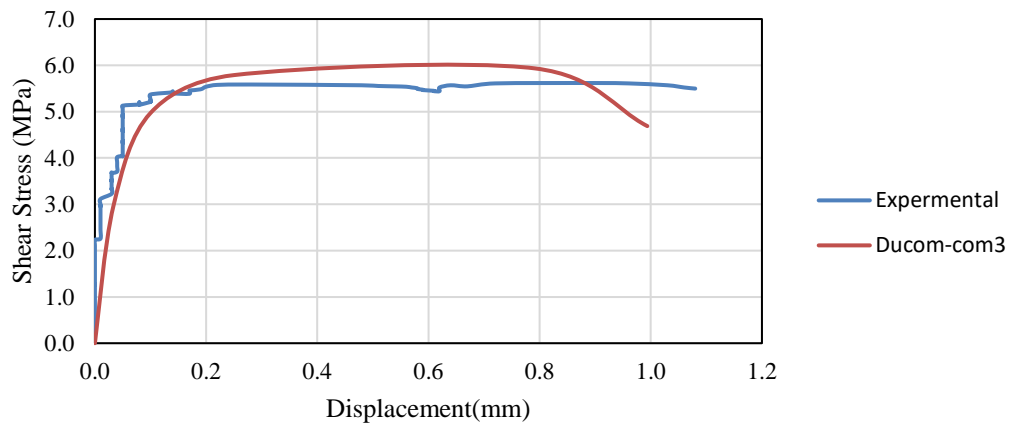


Figure 5-3: Shear strength of monotonically cast sample with monotonic loading (DuCOM-COM3)

From the above two models, the shear model was similar to the experimental program. From the experimental program for the sample tested the maximum stress of the sample was 5.856MPa and from Ducom-com3 it was 5.934.

The preliminary simulation result indicates that, the analytical tool may be used as a potential framework to future studies in the interface behaviour of concrete cast at different age. In the future more data needs to be collected and will be a target for future research.

CHAPTER 6 CONCLUSION AND RECOMMENDATIONS

6.1 Conclusions

6.1.1 Conclusions for Shear Strength

- It was observed from this experimental program that the presence of an interface between old and new concrete causes a reduction of shear and tensile strength. For shear specimen a reduction in shear strength of 77.39%,54.07% and 38.92% for without confinement,100 $\mu\epsilon$ and 125 $\mu\epsilon$ initial confinement strain respectively.
- The presence of water also has an adverse effect on the shear strength of concrete with a reduction of up to 10%, however the reduction decreases with increase of confinement.
- It was also observed, for monolithically cast samples due to increasing confining strain from without confining strain to 100 $\mu\epsilon$, significantly increases the interfacial shear strength of 53.37 %. And increasing initial confinement strain from without confining strain to 125 $\mu\epsilon$ increases the interfacial shear strength by 69.84 % and increasing initial confinement strain from 100 $\mu\epsilon$ to 125 $\mu\epsilon$ increases by 10.74%. For wet condition increasing initial confinement strain from 100 $\mu\epsilon$ to 125 $\mu\epsilon$ increases by 17.36%.
- It was also observed, for cast with interface samples due to increasing initial confining strain from without confining strain to 100 $\mu\epsilon$,significantly increases the interface shear strength 211.60 %,and increasing from without confining bar to 125 $\mu\epsilon$ increases the interface shear strength by 358.85 %,and increasing from 100 $\mu\epsilon$ to 125 $\mu\epsilon$ increases by 47.25%.For wet condition increasing initial confinement strain from 100 $\mu\epsilon$ to 125 $\mu\epsilon$ increase by 62.50%.from this and above conclusion the effect of confinement is larger for cast with interface specimens than monolithically cast samples.
- The experiment done indicated that the presence of an interface between old and new concrete reduces the tensile capacity of concrete by 50%-70%. A solid conclusion could not be made due to the limited sample tested.
- From the mapped surface roughness profile, as the mean roughness (R_a) increases the interface shear strength also increases.

- For monolithically cast shear sample model using DuCOM-COM3 based on the experimental program conducted. The model fairly predicted the peak load.

6.2 Recommendation

- Great care must be taken while maintaining concrete structure on interface zone. Since it was observed a reduction up to 77.39% for shear strength and reduction up to 70% for tensile strength.
- Future studies regarding the maintenance of concrete structures are required.
- Since roughness has a large effect on Interface strength. substrata concrete should be checked for various roughness by varying roughness.
- More modified digital processing or practical issues, an automated device can be designed and used to map the surface roughness and calculate the roughness coefficients and related Interface strength for shear and tension.
- Interface strength reduction should study with the reinforced concrete level slab, beams and columns.

REFERENCES

- Bogdan, N. (1985). *Multiparameter representation of surface roughness*. (Vol. 102). Warsaw Technical university, warsaw(Poland).
- Chhorn, C., Hong, S. J., & Lee, S. W. (2018). *Relationship between compressive and tensile strengths of roller-compacted concrete*. 5(3), 215–223. Retrieved from Department of Civil Engineering, Gangneung-Wonju National University, Republic of Korea
- Courard, L., Bissonnette, B., & Garbacz, A. (2015). *Concrete surface engineering*. London and New York: Taylor and Francis Group.
- Espeche, A. D., & León, J. (2011). *Estimation of bond strength envelopes for old-to-new concrete interfaces based on a cylinder splitting test*. 25(3), 1222–1235.
- F. AlHallaq Ahmed. (2014). *Improving Bond Strength Between Concrete Over Layers*. The University of Gaza, Palestine.
- Ghaffar, A.-S., Chaudhry, M. A., & Kamran, A. (2015). A new approach for the determination of tensile and shear strengths of normal weight concrete. *IOSR Journal of Engineering (IOSRJEN) Wwww.Iosrjen.Org ISSN, 05(08)*, 1–38. Retrieved from www.iosrjen.org
- Graybeal, B. (2006). *Material Property Characterization of Ultra-High Performance Concrete*. George town , Washington DC , United States: Turner-Fairbank Highway Research Center 6300.
- Maekawa, K., Ishida, T., Chijiwa, N., & Fujiyama, C. (2012). *Multi-Scale and Multi-Chemo Mechanistic Approach to The Life Cycle Performance Assesment of Structural Concrete*. (December 2012), Yokohama National university, Japan.
- Mattock, A. H. (1969). *Shear transfer under monotonic loading, across an interface between concretes casted at different time*. University of Washington.
- Qiao, P., & Zhou, Z. (2018). *Direct Tension Test Method for Characterization of Tensile Behavior of Ultra High Performace Concrete (UHPC)*. Washington.

- Ros, S., & Shima, H. (2013). *Relationship Between Splitting Tensile Strength and Compressive Strength of Concrete At Early Age With Different Types of Cements and Curing Temperaturehistories*. *13th annual convention of japan Concrete Institute*, 35(1), 427–432.
- Santos, D., & Pedro, D. (2009). *Assessment of the shear strenght between concrete layers*. Thesis submitted in fulfilment of the requirements for the degree of Doctor of Philosophy in Civil Engineering, specialty of Mechanics of Structures and Materials universty of coimbra ,Portugal.
- Santos, Pedro M.D., & Júlio, E. N. B. S. (2014). Interface Shear Transfer on Composite Concrete Members. *ACI Structural Journal*, 111(1), 113–121.
- Santos, Pedro Miguel Duarte, & Julio, E. N. B. S. (2011). *Factors affecting bond between new and old concrete*. *ACI Materials journal*(4), 449–456.
- Solomon, Y. (2018). *Assessment of degradation on the interface of concretes cast at different times Subjected to cyclic shear loading in dry and moist condition*. Thesis presented to Addis Ababa Instute of Technology, at Addis Ababa, Ethiopia, In Partial Fulfilment of the Requirement for the Degree of Master of Science.
- Tadesse, L., Seifu, N., Gebeyehu, B., Ababu, H., & Tesfaye, K. (2018). *An Experimental Study On The Tensile Capacity Of Concrete At An Interface Tested At Dry And Wet Condition*, Thesis presented to Addis Ababa Instute of Technology, at Addis Ababa, Ethiopia, In Partial Fulfilment of the Requirement for the Degree of Bachelor of Science.
- Walraven, J. . (1997). *Aggregate interlock: A theoretical and Expermental Analysis*. Universty of Delft, Netherlands.
- Wan, Z., & Shin, H. (2010). *Interfacial shear bond strength between old and new concrete*. Korea Concrte Institue.
- Zerabruck, F. (2015). *Experimental Investigation of Construction Joint in RC beams*. Thesis presented to Addis Ababa Instute of Technology, at Addis Ababa, Ethiopia, In Parttia Fulfilment of the Requirement for the Degree of Master of Science.

APPENDIX

APPENDIX A

A1. Compressive strength result of monolithically cast sample for shear specimen

Designation	Specimen	Cube number	Failure load (kN)	Compressive strength (MPa)	Cubic Mean compressive strength (MPa)	Coefficient of variation (%)
MSD-1	Control	1	960.100	42.630	41.57	3.62%
		2	912.200	40.500		
MSD-2	Control	1	888.400	39.450	44.232	5.78%
		2	1055.700	46.920		
		3	991.300	44.060		
		4	1005.300	44.680		
		5	1002.800	44.550		
		6	1028.800	45.730		
MSD-3	Control	1	938.100	41.610	38.965	5.73%
		2	838.700	37.280		
		3	831.500	36.960		
		4	900.400	40.010		
MSD-4	Control	1	873.200	37.210	37.757	2.91%
		2	877.900	39.020		
		3	833.400	37.040		
MSD-5	Control	1	853.900	37.950	36.920	10.40%
		2	714.300	31.750		
		3	921.700	40.970		
		4	832.700	37.010		
MSW-6	Control	1	845.000	37.550	38.028	2.86%
		2	885.500	39.360		
		3	863.300	38.370		
		4	828.700	36.830		
MSW-7	Control	1	827.900	36.790	39.227	5.38%
		2	910.600	40.470		
		3	909.400	40.420		
MSW-8	Control	1	949.100	42.180	41.820	2.42%
		2	909.100	40.400		
		3	947.100	41.930		
		4	962.200	42.770		
MSD-9	Control	1	819.700	36.430	36.160	0.89%
		2	803.400	35.700		
		3	817.100	36.320		
		4	814.300	36.190		

A2. Compressive strength result of cast with interface sample for shear specimen

Designation	Specimen	Cube number	Failure load(kN)	Compressive strength (MPa)	Cubic Mean compressive strength (MPa)	Coefficient of variation (%)
BSD-1	substrata	1	899.000	39.950	43.077	5.09%
		2	1020.000	45.330		
		3	1013.200	45.030		
		4	997.600	44.330		
		5	959.300	42.640		
		6	926.500	41.180		
	Overlay	1	622.100	27.665	29.525	6.07%
		2	667.700	29.670		
		3	703.100	31.240		
BSD-2	Substrata	1	806.800	35.860	35.968	5.18%
		2	810.200	36.010		
		3	758.700	33.720		
		4	861.200	38.280		
	Overlay	1	736.900	32.750	33.333	5.62%
		2	715.900	31.820		
		3	797.100	35.430		
BSD-3	Substrata	1	1021.900	45.420	45.144	4.16%
		2	979.000	43.290		
		3	1046.700	46.520		
		4	1065.800	47.230		
		5	973.400	43.260		
	Overlay	1	627.800	27.900	29.033	6.35%
		2	630.900	28.040		
		3	701.200	31.160		
BSD-4	Substrata	1	907.400	40.330	41.492	4.66%
		2	970.100	43.110		
		3	884.200	39.300		
		4	973.200	43.250		
		5	935.600	41.470		
	Overlay	1	769.400	34.190	29.820	13.06%
		2	601.298	26.720		
		3	642.400	28.550		

Experimental Investigation on Interface Shear and Tensile Strength Between old and New Concrete at Different Moisture Condition

BSD-5	Substrata	1	930.600	41.240	39.682	4.44%
		2	897.400	39.890		
		3	881.100	39.160		
		4	843.300	37.480		
		5	914.400	40.640		
	Overlay	1	839.000	37.290	35.440	5.14%
2		796.100	35.380			
3		757.300	33.650			
BSD-6	Substrata	1	930.600	41.240	39.682	4.44%
		2	897.400	39.890		
		3	881.100	39.160		
		4	843.300	37.480		
		5	914.400	40.640		
	Overlay	1	839.000	37.290	35.440	5.14%
2		796.100	35.380			
3		757.300	33.650			
BSW-7	Substrata	1	772.100	34.310	32.922	6.88%
		2	669.600	29.760		
		3	708.600	31.490		
		4	699.900	31.110		
		5	853.700	37.940		
	Overlay	1	772.300	34.320	34.240	2.52%
2		795.200	35.340			
3		766.200	34.050			
4		749.900	33.250			
BSW-8	Substrata	1	856.000	38.050	35.993	6.73%
		2	751.400	33.400		
		3	856.300	38.060		
		4	775.600	34.460		
	Overlay	1	682.300	30.330	31.284	6.21%
		2	765.700	34.030		
3		646.500	28.720			
4		708.800	31.500			
5		716.400	31.840			
BSW-9	Substrata	1	738.300	32.810	34.158	3.57%
		2	794.100	35.290		
		3	743.300	33.030		
		4	788.700	35.050		
		5	778.700	34.610		
	Overlay	1	823.700	36.610	38.295	5.35%
2		851.400	37.840			
3		934.000	41.270			
4		842.800	37.460			

Experimental Investigation on Interface Shear and Tensile Strength Between old and New Concrete at
Different Moisture Condition

BSW-10	Substrata	1	859.900	38.210	39.384	2.51%
		2	860.200	38.230		
		3	906.200	40.280		
		4	876.100	38.940		
		5	928.400	41.260		
	Overlay	1	949.100	42.180	41.820	2.42%
		2	909.100	40.400		
		3	947.100	41.930		
		4	962.200	42.770		
BSD-11	Substrata	1	759.800	33.770	33.200	2.80%
		2	719.800	31.990		
		3	741.800	32.970		
		4	766.700	34.070		
	Overlay	1	872.000	38.760	36.826	4.557%
		2	808.000	35.910		
		3	805.500	35.800		

APPENDIX B

B1. Compressive strength result of cast with interface for tensile specimen

Designation	Specimen	Cube number	Failure load (kN)	Compressive strength (MPa)	Cubic Mean compressive strength (MPa)	Coefficient of variation (%)
MTD-1	Control	1	866.400	38.510	38.640	0.48%
		2	876.200	38.770		
MTD-2	Control	1	754.200	33.520	31.735	7.95%
		2	673.900	29.950		
MTD-3	Control	1	866.400	38.510	38.590	0.29%
		2	870.000	38.670		
MTD-4	Control	1	923.800	41.060	40.703	2.03%
		2	894.700	39.760		
		3	929.000	41.290		
MTD-5	Control	1	858.000	38.130	37.085	3.99%
		2	811.100	36.040		
MTD-6	Control	1	844.100	39.520	39.060	1.67%
		2	868.500	38.600		

B2. Compressive strength result of cast with interface for tensile specimen

Designation	Specimen	Cube number	Failure load (kN)	Compressive strength (MPa)	Cubic Mean compressive strength (MPa)	Coefficient of variation (%)
BTD-1	Substrata	1	866.400	38.510	38.640	0.48%
		2	876.200	38.770		
	Overlay	1	754.200	33.520	31.735	7.95%
		2	673.900	29.950		
BTD-2	Substrata	1	866.400	38.510	38.590	0.29%
		2	870.000	38.670		
	Overlay	1	923.800	41.060	40.703	2.03%
		2	894.700	39.760		
		3	929.000	41.290		
BTD-3	Substrata	1	858.000	38.130	37.085	3.99%
		2	811.100	36.040		
	Overlay	1	844.100	39.520	39.060	1.67%
		2	868.500	38.600		

B3. Cylindrical strength result of cast with interface sample for tensile specimen

Designation	Specimen	Cylinder number	Failure load (kN)	Splitting tensile strength (MPa)	Mean splitting tensile strength (MPa)	Coefficient of variation (%)
MTD-1	Control	1	256.700	3.632	3.856	5.55%
		2	274.200	3.879		
		3	286.800	4.057		
MTD-2	Control	1	213.100	3.015	3.065	1.59%
		2	216.800	3.067		
		3	220.000	3.112		
MTD-3	Control	1	264.800	3.746	3.839	2.09%
		2	274.200	3.879		
		3	275.000	3.890		
MTD-4	Control	1	275.000	3.890	3.956	1.70%
		2	279.400	3.953		
		3	284.500	4.025		
MTD-5	Control	1	248.900	3.521	3.579	1.51%
		2	253.500	3.586		
		3	256.500	3.629		
MTD-6	Control	1	256.700	3.632	3.752	3.30%
		2	264.800	3.746		
		3	274.200	3.879		