BOND STRENGTH BEHAVIOUR OF FLY ASH AND GROUND GRANULATED BLAST FURNACE SLAG OF GEOPOLYMER CONCRETE

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DEDICATION

This thesis is dedicated to my parents, who taught me that the best kind of knowledge to have is that which is learned for its own sake. It is also dedicated to my siblings and fellow friends, who taught me that even the largest task can be accomplished if it is done one step at a time.

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ABSTRACT

As of recently, research on geopolymer concrete (GPC) is gaining popularity among construction practitioners and researchers due to its green materials in construction applications. Geopolymer is the result of a chemical reaction between source materials such as fly ash and ground granulated blast furnace slag (GGBFS), and alkaline liquid. It could fully replace Ordinary Portland cement (OPC) in the manufacturing of concrete products and thus reduce the negative impact of the carbon footprint (CO_2) on the environment. At present, most of the researches on GPC are mainly focused on the concrete design mix, mechanical properties and other related structural applications such as the cracking mode, flexural and shear behaviour and deflection of GPC. This study focuses on the bond strength behaviour of GPC, which is vital in predicting the cracking mode and behaviour. The main objective of this study is to evaluate parameters controlling the bond strength behaviour of GPC such as compressive strength, concrete cover-to-diameter (c/d) ratio and embedment length. Prior to the experiment, the design mix for the specimens was achieved on trial-and-error method by applying 0 %, 10 % and 20 % GGBFS on the fly ash-based GPC basis to obtain concrete grade of 20, 30 and 40 respectively with OPC as control specimens. All specimens were casted on 100 mm and 150 mm dimensional cube moulds and activated using sodium-based alkaline solution. Fly ash-based GPC specimens were heat cured (60 °C) for 24 hours whereas specimens partially replaced with GGBFS were ambient cured. For bond specimens, the c/d ratio was varied from 4.19 to 7.0 whereas 3.5d and 5.0d for embedment using bond breaker. Overall pull-out tests show that the normalised bond strength for GPC decreased as the concrete grade increased with GPC over OPC concrete. For c/d ratio, there was no significant effect on bond strength for both concrete as the ratio was increased more than 5.75. Specimens with higher embedment length also show reduction in bond strength. In order to further promote the use of environmentally friendly GPC in the construction industry, further structural assessment on the optimum bond strength of GPC needs to be carried out.

ABSTRAK

Baru-baru ini, penyelidikan konkrit geopolimer (GPC) mendapat populariti dalam kalangan pengamal pembinaan dan penyelidik kerana bahan hijau yang terdapat padanya dalam aplikasi pembinaan. Geopolimer merupakan hasil reaksi antara bahan sumber seperti debu terbang dan sanga relau bagas berbutir tanah (GGBFS) dengan cecair alkali. Bahan ini boleh menjadi penggantian penuh bagi simen Portland biasa (OPC) untuk menghasilkan produk konkrit sekaligus mengurangkan impak negatif daripada jejak karbon (CO_2) terhadap alam sekitar. Pada masa kini, kebanyakan kajian menekankan campuran tereka bentuk, sifat mekanikal dan aplikasi struktur yang lain termasuklah mod retak, tingkah laku lentur dan ricih, dan juga pesongan untuk GPC. Kajian ini difokuskan kepada tingkah laku kekuatan ikatan GPC, yang penting dalam meramal mod dan tingkah laku retak. Objektif utama kajian ini adalah untuk menilai parameter mengawal tingkah laku kekuatan ikatan GPC seperti kekuatan mampat, nisbah penutup konkrit-diameter (c/d) dan panjang pembenaman. Berikutan itu, campuran tereka bentuk untuk spesimen dicapai berdasarkan kaedah percubaan dengan mengaplikasi 0 %, 10 % dan 20 % GGBFS kepada GPC berasaskan debu terbang untuk memperoleh gred konkrit, masing-masing 20, 30 dan 40 dengan konkrit OPC sebagai spesimen kawalan. Semua spesimen dituang ke dalam acuan kiub berdimensi 100 mm dan 150 mm dan diaktifkan menggunakan larutan alkali berasaskan natrium. Spesimen GPC berasaskan abu terbang diawet menggunakan haba (60°C) selama 24 jam, manakala spesimen menggunakan GGBFS sebagai pengganti separa diawet dalam suhu sekitar. Untuk spesimen ikatan, nisbah c/d divariasikan daripada 4.19 kepada 7.0 manakala 3.5d dan 5.0d untuk panjang pembenaman menggunakan pemecah ikatan. Keputusan keseluruhan ujian tarik-keluar menunjukkan kekuatan ikatan ternormal bagi kedua-dua konkrit G30 menurun selepas gred konkrit ditingkatkan dengan GPC mengatasi konkrit OPC. Untuk nisbah c/d, tiada kesan signifikan pada kekuatan ikatan untuk kedua-dua konkrit selepas nisbah tersebut ditingkatkan melebihi 5.75. Spesimen dengan panjang pembenaman yang tinggi juga menunjukkan pengurangan dalam kekuatan ikatan. Untuk menggalakkan penggunaan GPC yang mesra alam dalam industri pembinaan, lanjutan penilaian struktur terhadap kekuatan ikatan optimum menggunakan GPC perlu dijalankan.

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LIST OF ABBREVIATIONS

RC	-	Reinforced Concrete
OPC	-	Ordinary Portland Cement
GPC	-	Geopolymer Concrete
IPC	-	Inorganic Polymer Concrete
CO_2	-	Carbon Dioxide
C-S-H	-	Calcium Silicate Hydrate
C-A-S-H	-	Calcium Aluminate Silicate Hydrate
SiO_2	-	Silicon Dioxide
Al_2O_3	-	Aluminium Oxide
Fe_2O_3	-	Iron (II) Oxide
CaO	-	Calcium Oxide
SEM	-	Scanning Electron Microscopy
XRF	-	X-Ray Fluorescence
HVFA	-	High Volume Fly Ash
GGBFS	-	Ground Granulated Blast Furnace Slag
POFA	-	Palm Oil Fuel Ash
MARS	-	Multivariable Adaptive Regression
ANN	-	Artificial Neural Networks
ASTM	-	American Society for Testing and Materials
MS	-	Malaysia Standard
RILEM	-	International Union of Laboratories and Experts in Construction Materials, Systems and Structures
BS	-	British Standard
UTM	-	Universal Testing Machine
GFRP	-	Glass Fibre Reinforced Polymer
PI	-	Partial Interaction
NaOH	-	Sodium Hydroxide
Na_2SiO_3	-	Sodium Silicate
SSD	-	Saturated-Surface Dry
LVDT	-	Linear Variable Displacement Transducer

LIST OF SYMBOLS

τ_u	-	Ultimate bond strength
τ_{norm}	-	Normalised bond strength
F	-	Force
d	-	Diameter of steel reinforcement
L	-	Embedment length
δ	-	Slip
δ_1	-	Slip at ultimate bond stress
c/d	-	Concrete cover-to-diameter ratio
sp/b	-	Superplasticiser-to-binder ratio
f'_c	-	Compressive strength
f'_{ct}	-	Splitting tensile strength
f_{yk}	-	Steel yield strength
f_t	-	Steel tensile strength
l_d	-	Development length
CA:FA	-	Coarse aggregates-to-fine aggregates ratio
w/b	-	Water-to-binder ratio
$\tau–\delta$	-	Bond stress-slip
$P–\Delta$	-	Load-slip

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CHAPTER 1

INTRODUCTION

1.1 Background of Study

Development of civil infrastructures including multi-storey buildings, road, bridges, retaining wall and underground structures are synonym with the reinforced concrete (RC) as one of the most widely utilized composite materials (Maranan, 2016). In designing and analysing RC members, knowledge of bond between reinforcement and its concrete surrounding is crucial since it could affect flexural behaviour as well as the shear capacity of the members (Visintin *et al.*, 2013). Also termed as bond behaviour, the concrete structure consisted of tensile stress transferred from steel-to-concrete by interfacial interaction. The mechanism is important not only to govern the formation of cracks and crack width but also for many other vital issues related to structural application such as anchorage capacity, minimum development length and lap splice length of the reinforcements (Visintin *et al*., 2013; Orangun *et al*., 1977).

When reinforcement is embedded in concrete and tested in tension, concrete cracks due to the failure of chemical adhesion that has been formed during hardening of concrete. Thus, adequate bonding between concrete and steel is essential to ensure the effective composite action of the RC section (Selby, 2012). Research on bond strength in RC components was widened into various structural applications including the tension stiffening and deflection through experimental, analytical and even numerical methods (Visintin *et al*., 2013). Recently, the structural applications utilized various by-products such as fly ash and ground granulated blast furnace slag (GGBFS) as alternative sources of binder to produce geopolymer concrete (GPC), and could be potentially used as construction materials (Albitar *et al*., 2018; Ma *et al*., 2018).

The fundamental studies on structural applications, bond behaviour, still needs further investigation for GPC utilizing both by-products due to limited knowledge on the material properties of the materials. Plus, knowledge on its mechanism needs to be well-understood as it is the critical factor governing the bond performance of RC components. It includes the parameters such as compressive strength, concrete cover-to-diameter (c/d) ratio and embedment length that could effect on the bond strength of GPC (Zhao *et al*., 2016). Thus, this study will apply fly ash and GGBFS as the by-products to investigate the bond strength behaviour for GPC in terms of material properties thus propose the utilization of this green concrete to be used in construction applications.

1.2 Problem Statement

Ordinary Portland cement (OPC) as conventional concrete in RC structure is well-known for its excessive carbon footprint to the environment (Razi *et al*., 2016). Each tonne of cement production releases approximately one tonne of carbon dioxide (CO_2) to the surrounding environment. Annually, around 5 % to 7 % of worldwide's CO_2 emission was contributed by the cement industry (Alnahhal *et al*., 2017). Furthermore, cement manufacturing is a resource-intensive and energy-intensive process (Olivier *et al*., 2012). Currently, researchers are aiming to develop more effective alternatives, including replacement of Ordinary Portland cement (OPC) with geopolymer concrete (GPC) (Muttashar *et al*., 2014).

Also, there is a massive amount of Class F fly ash production from energy generation, which requires an enormous amount of space for its disposal (Islam *et al*., 2015). Class F fly ash is more preferred compared to Class C fly ash due to its higher workability and ease of handling as construction materials (Chou *et al*., 2009). However, there are some issues associated with the utilization of the fly ash-based GPC including low early strength development as well as inclusion of high temperature curing which requires higher energy consumption (Nath and Sarker, 2014). To improve such issues, ground granulated blast furnace slag (GGBFS) could be suggested as partial replacement of the GPC (Fang *et al*., 2018).

Many studies have been carried out to investigate bond strength between concrete and reinforcement that could contribute to the ultimate bond stress and slip for conventional concrete (Ganesan *et al*., 2015; Ma *et al*., 2018; Mendis and French, 2000; Mo *et al*., 2016; Tekle *et al*., 2016; Vinothini *et al*., 2015). However, the studies are not considered extensive for GPC in terms of parameters affecting the bond strength, thus need additional studies on its material properties as well as bond behaviour. Utilization of the by-products as replacement for conventional concrete could be ideal to investigate the bond behaviour of fly ash and GGBFS-based GPC (Fang *et al*., 2018).

Despite safer design basis for engineers in dealing with splitting failures and improved prediction of cracking behaviour for RC members, the experimental works on bond behaviour utilizing the GPC still need further investigation. Thus, the utilization of Class F fly ash and GGBFS could be the most ideal by-products to investigate the material properties as well as bond strength of GPC. Therefore, this strongly indicates important gaps to be fulfilled in proposing utilization of GPC for future research as sustainable concrete in construction applications.

1.3 Research Objectives

The objectives of the research are:

(a) To identify compressive strength, concrete cover-to-diameter (c/d) ratio and embedment length as the parameters controlling bond strength between GPC and embedded reinforcement.

(b) To evaluate the bond strength for GPC made up of Class F fly ash and GGBFS embedded with reinforcement based on the parameters identified.

(c) To propose utilization of Class F fly ash and GGBFS as GPC for further structural applications.

1.4 Scope of Research

In this study, Class F fly ash is the main binder in GPC with GGBFS as the partial replacement. Unlike OPC as the well-established materials, fly ash needed to undergo chemical analysis for identification of either Class F or Class C fly ash. For current study, the analysis includes X-ray fluorescent (XRF) analysis for the identification as well as comparison with previous studies. Then, GGBFS were added in percentage of 0 %, 10 % and 15 % as fly ash replacement in GPC.

Trial-and-error design mixture is performed to obtain a suitable design mixture based on compressive test, splitting tensile test as well as slump test, subjected to bond test. For bond behaviour, the bond test that was conducted is pull-out test. OPC concrete as control specimens is fabricated with GPC as comparison purpose. All tests were conducted for 7 days curing ages. The specimens were casted into either 100 mm-dimensional or 150mm-dimensional cube mould and cured at ambient temperature, except for fly ash-based GPC that requires heat curing.

1.5 Significance of Study

The utilization of Class F fly ash and GGBFS as the main binder in GPC could be as effective as conventional concrete in structural application. For instance, in terms of bond strength, some of previous studies suggested that both concretes are comparable to each other despite differences in material properties (Castel and Foster, 2015; Sofi *et al*., 2007; Junaid *et al*., 2015; Tekle *et al*., 2016). Other than the structural aspects, sustainability, efficiency and productivity of utilization for by-products should also be taken into consideration in order to produce a more sustainable environment by reducing the utilization of conventional concrete (Razi *et al*., 2016). Class F fly ash and GGBFS were well-known as the main by-products to manufacture GPC and could be promoted to replace the conventional concrete in the future (Fang *et al*., 2018; Sani *et al*., 2020).

Inclusion of GGBFS could be helpful in attaining a higher compressive strength since Class F fly ash could not achieve a high compressive strength at an early age. Plus, compressive strength portrays the material properties of GPC in which eventually affect the bond strength (Al-Azzawi *et al*., 2018). Other than compressive strength, bond strength prediction of GPC governed by c/d ratio and embedment length could be developed. The experimental bond strength based on all the parameters could suggest optimum bond strength as a safe design value to be proposed, especially for different type of materials as relative comparison (Orangun *et al*., 1977).

This study will also provide experimental investigation of bond strength to represent bond-slip behaviour by carrying out pull-out tests utilizing GPC to propose the utilization of this green cement as construction materials. Upon its completion, the results will be compared with control specimens and previous bond strength equations to give predictions on the optimum bond strength with the parameters involved. The experimental analysis could assist designers to propose an equation as a guideline for further structural application, especially when it comes to non-established materials such as Class F fly ash and GGBFS. Also, this study could be a benchmark for extension studies of tension stiffening and deflection behaviour of GPC in structural application (Visintin *et al*., 2013).

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Appendix A   Photos of Research Materials and Process

Figure A1   Collected Class F fly ash sample

Figure A2   Collected GGBFS sample

Figure A3 Collected OPC sample

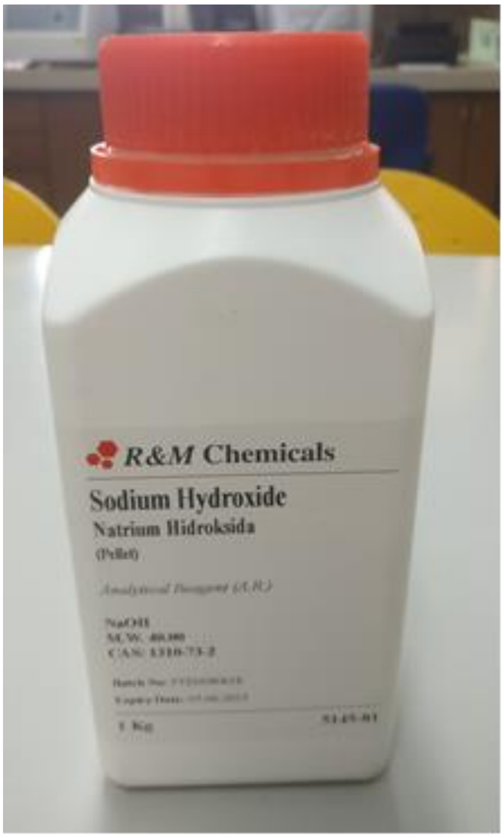


Figure A4 Sodium hydroxide flakes supplied by BTScience Sdn. Bhd.

Figure A5 Sodium silicate gel supplied by BTScience Sdn. Bhd.

Figure A6 Alkaline solution with 14 M concentration

Figure A7   Sikadur-30 used to prepare the bond breaker

Figure A8   Bond breaker prepared for pull-out specimens

Figure A9 Universal Testing Machine for compressive and splitting tensile test

Figure A10 Universal Testing Machine for steel tensile test

Figure A11 Universal Testing Machine for pull-out test

Figure A12 Linear Variable Displacement Transducer (LVDT)

Figure A13 Materials to manufacture GPC specimens

Figure A14 56-L capacity pan mixer

Figure A15 Workability test for GPC

Figure A16 Poker vibrator used to compact the fresh GPC

Figure A17 Dry oven curing for GPC

Figure A18 GPC specimens after heat cured and de-moulded

Figure A19 In-situ casting for 100 mm dimensional pull-out specimen

Figure A20 In-situ casting for 150 mm dimensional pull-out specimen

Figure A21 Pull-out specimen after de-moulding (a) 100 mm dimensional

Figure A22 Pull-out specimen after de-moulding (a) 100 mm dimensional

Figure A23 Experimental compressive strength test setting

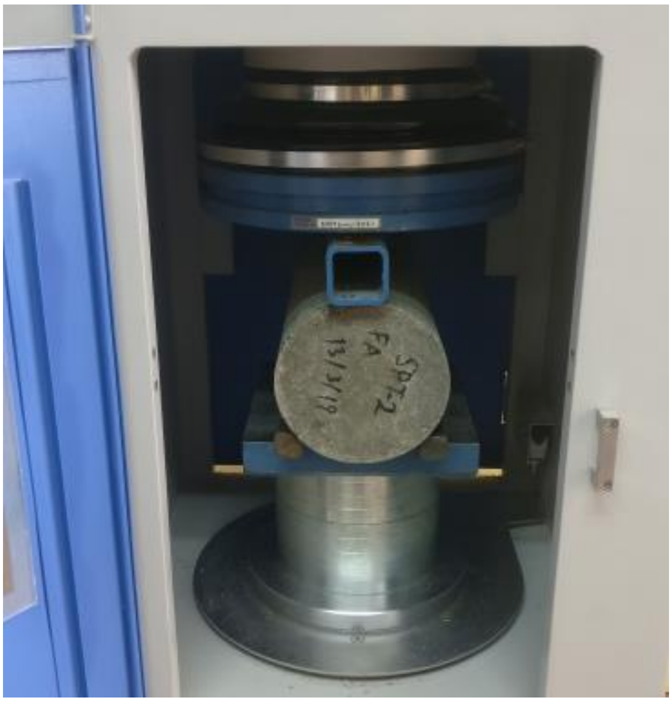
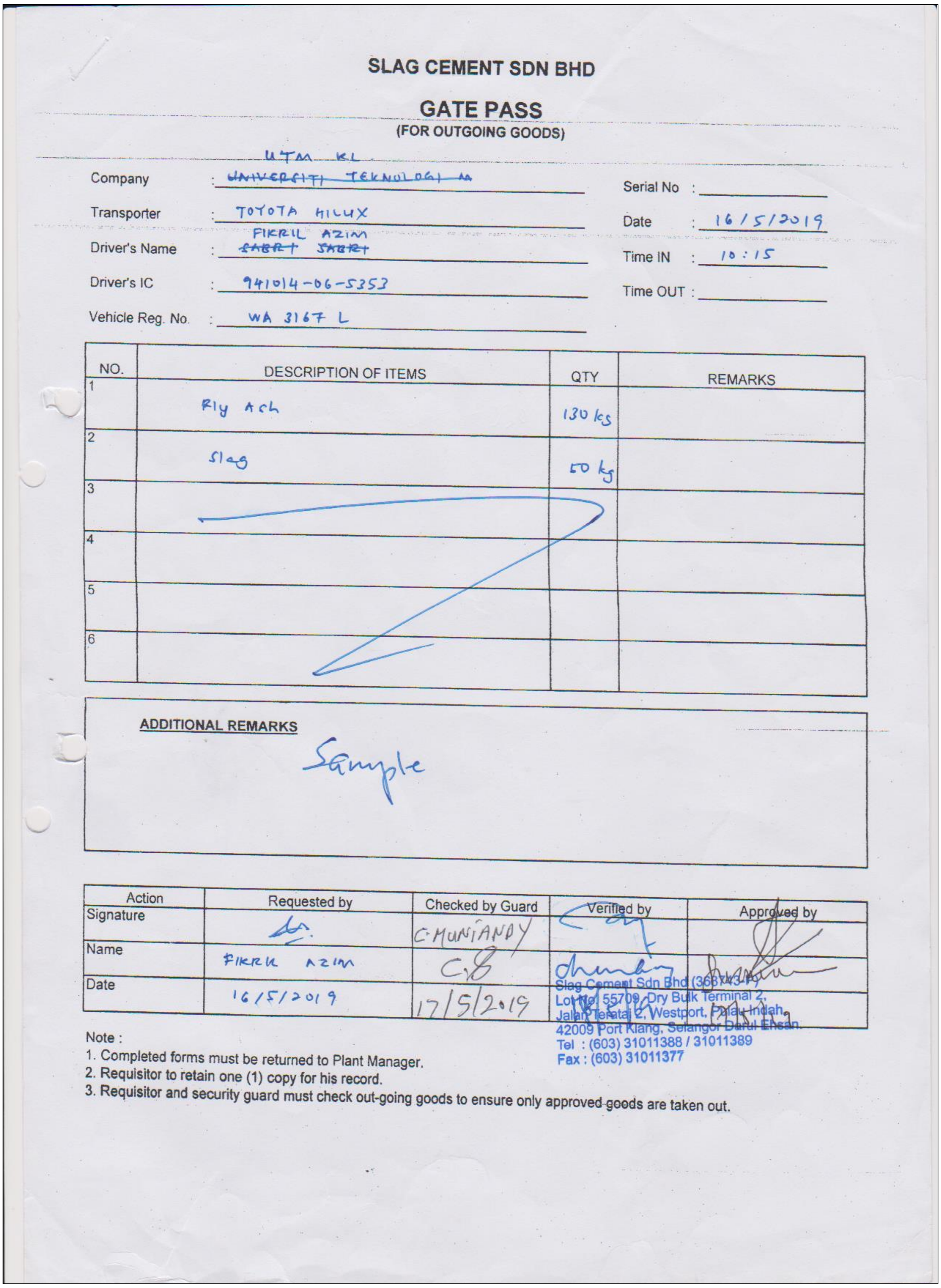


Figure A24 Experimental splitting tensile test setting

Figure A25 Experimental pull-out test setting

Figure A26 Gypsum applied before pull-out test



SLAG CEMENT SDN BHD

GATE PASS

(FOR OUTGOING GOODS)

Company	: ~~UNIVERSITI TEKNOLOGI M~~ UTM KL	Serial No	:
Transporter	: TOYOTA HILUX	Date	: 16/5/2019
Driver's Name	: ~~SABRI SABRI~~ FIKRIL AZIM	Time IN	: 10:15
Driver's IC	: 941014-06-5353	Time OUT	:
Vehicle Reg. No.	: WA 3167 L		

NO.	DESCRIPTION OF ITEMS	QTY	REMARKS
1	Fly Ash	130 kg	
2	Slag	50 kg	
3			
4			
5			
6			

ADDITIONAL REMARKS

Sample

Action	Requested by	Checked by Guard	Verified by	Approved by
Signature	[signature]	C-MUNIANDY	[signature]	[signature]
Name	FIKRIL AZIM	[signature]	[signature]	[signature]
Date	16/5/2019	17/5/2019		

Slag Cement Sdn Bhd (366763-K)
Lot No. 55709, Dry Bulk Terminal 2,
Jalan Teratai 2, Westport, Pulau Indah,
42009 Port Klang, Selangor Darul Ehsan.
Tel : (603) 31011388 / 31011389
Fax : (603) 31011377

Note :
1. Completed forms must be returned to Plant Manager.
2. Requisitor to retain one (1) copy for his record.
3. Requisitor and security guard must check out-going goods to ensure only approved goods are taken out.

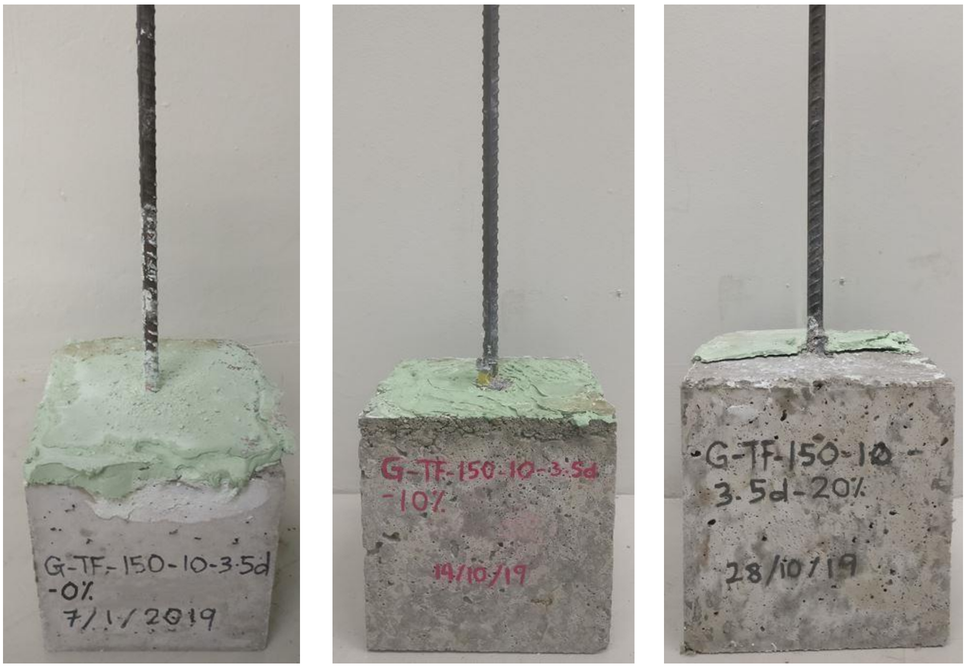
Figure A27 Fly ash and GGBFS collection form

(a) (b) (c)

Figure A28 G-TF-100-10-3.5d (a) 0 % GGBFS (b) 10 % GGBFS (c) 20 % GGBFS

(a) (b) (c)

Figure A29 G-TF-100-10-5.0d (a) 0 % GGBFS (b) 10 % GGBFS (c) 20 % GGBFS

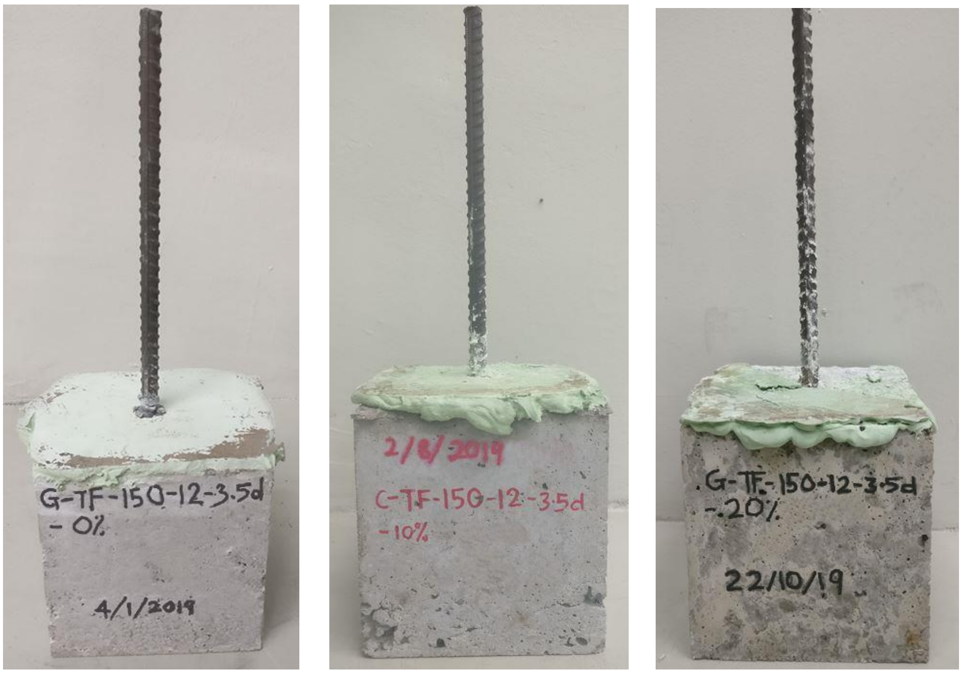


(a) (b) (c)

Figure A30 G-TF-150-10-3.5d (a) 0 % GGBFS (b) 10 % GGBFS (c) 20 % GGBFS

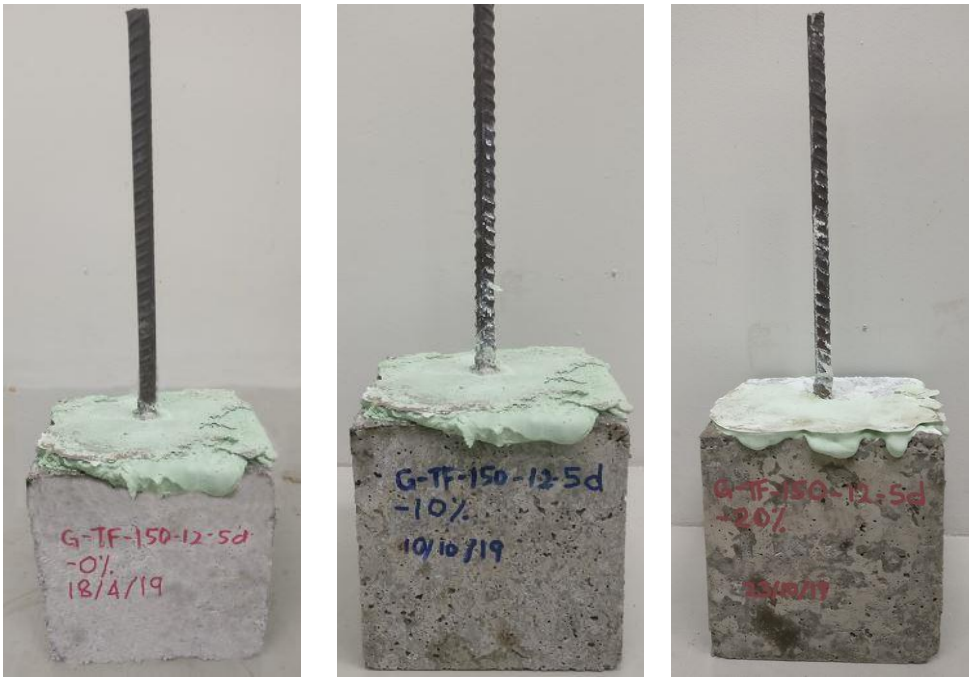
(a) (b) (c)

Figure A31 G-TF-150-10-5.0d (a) 0 % GGBFS (b) 10 % GGBFS (c) 20 % GGBFS



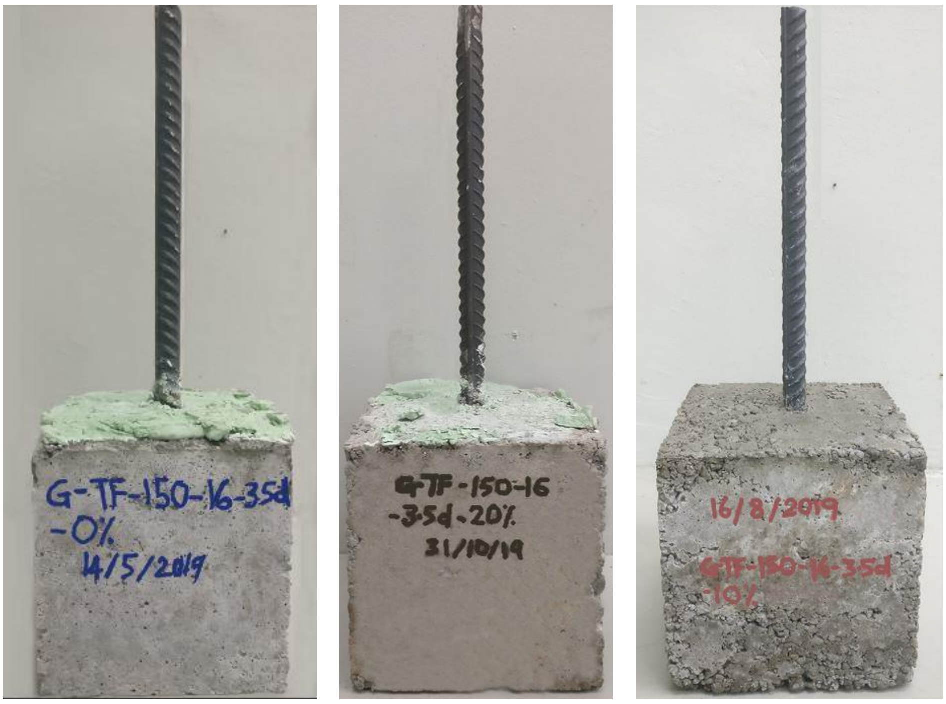
(a) (b) (c)

Figure A32 G-TF-150-12-3.5d (a) 0 % GGBFS (b) 10 % GGBFS (c) 20 % GGBFS



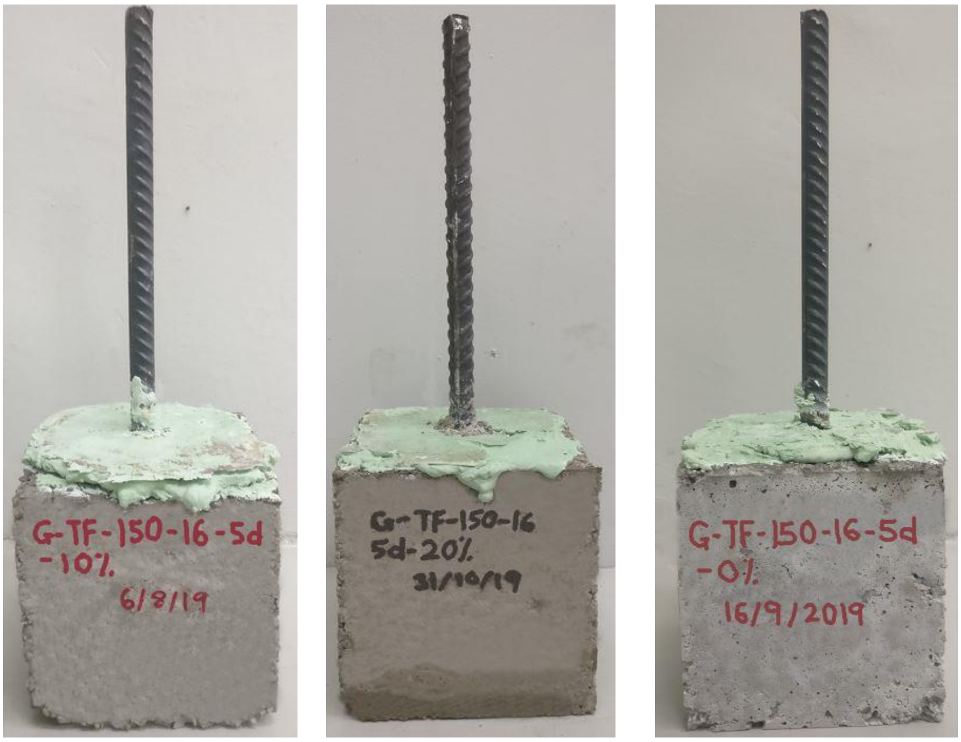
(a) (b) (c)

Figure A33 G-TF-150-12-5.0d (a) 0 % GGBFS (b) 10 % GGBFS (c) 20 % GGBFS



(a) (b) (c)

Figure A34 G-TF-150-16-3.5d (a) 0 % GGBFS (b) 10 % GGBFS (c) 20 % GGBFS

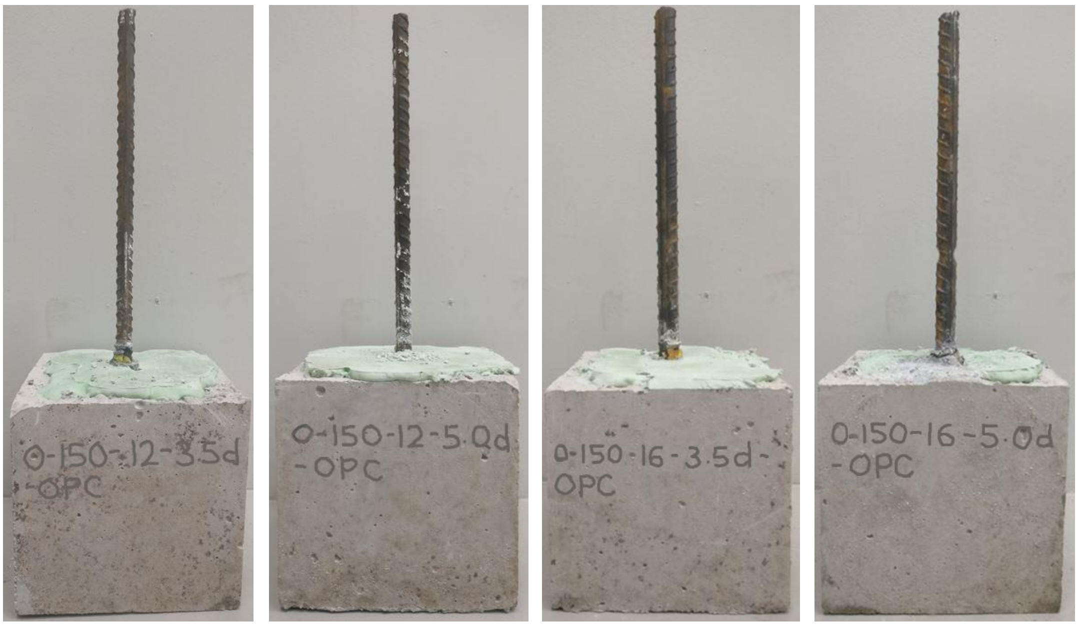


(a) (b) (c)

Figure A35 G-TF-150-16-5.0d (a) 0 % GGBFS (b) 10 % GGBFS (c) 20 % GGBFS

(a) (b) (c) (d)

Figure A36 (a) O-100-10-3.5d-OPC (b) O-100-10-5.0d-OPC (c) O-150-10-3.5d-OPC (d) O-150-10-5.0d-OPC



(a) (b) (c) (d)

Figure A37 (a) O-150-12-3.5d-OPC (b) O-150-12-5.0d-OPC (c) O-150-16-3.5d-OPC (d) O-150-16-5.0d-OPC

Appendix B Tensile Data for Steel Bar

Key Word		Product Name	
Test File Name		Method File Name	Azim Rod 10mm.xmux
Report Date	1/31/2019	Test Date	1/31/2019
Test Mode	Single	Test Type	Tensile
Speed	10mm/min	Shape	Rod
No of Batches:	1	Qty/Batch:	1

Name	Diameter	LASE1_Force	YP(%FS)_Force	YS1_Force
Parameters		Stroke 1 mm	0.1 %	0.2 %
Unit	mm	kN	kN	kN
Azim Rod 1	10.0000	1.09108	43.8549	-.-

Name	PointPicking1_Force	LYP_Force	Max_Disp_Force	Max_Force
Parameters				Calc. at Entire Areas
Unit	kN	kN	kN	kN
Azim Rod 1	-.-	43.2851	0.71843	49.0361

Name	Break_Force
Parameters	Sensitivity: 10
Unit	kN
Azim Rod 1	33.1168

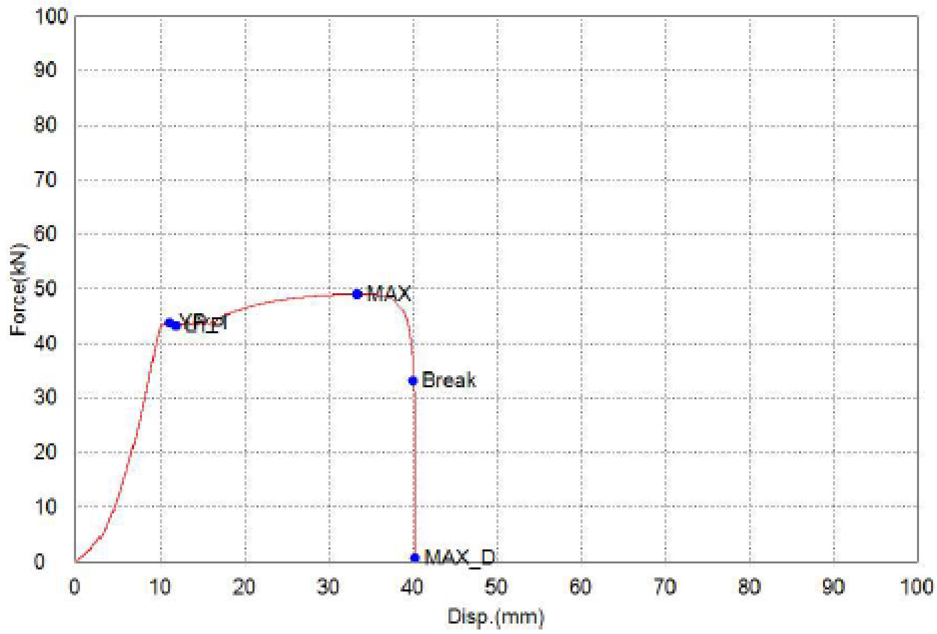


Figure B1 Tensile test result for 10 mm diameter

Key Word		Product Name	
Test File Name		Method File Name	Azim Rod 12mm.xmux
Report Date	1/31/2019	Test Date	1/31/2019
Test Mode	Single	Test Type	Tensile
Speed	10mm/min	Shape	Rod
No of Batches:	1	Qty/Batch:	1

Name	Diameter	LASE1_Force	YP(%FS)_Force	YS1_Force
Parameters		Stroke 1 mm	0.1 %	0.2 %
Unit	mm	kN	kN	kN
Azim Rod 2	12.0000	0.21919	51.2741	-.-

Name	PointPicking1_Force	LYP_Force	Max_Disp_Force	Max_Force
Parameters				Calc. at Entire Areas
Unit	kN	kN	kN	kN
Azim Rod 2	-.-	50.3579	46.1627	59.9980

Name	Break_Force
Parameters	Sensitivity: 10
Unit	kN
Azim Rod 2	46.6042

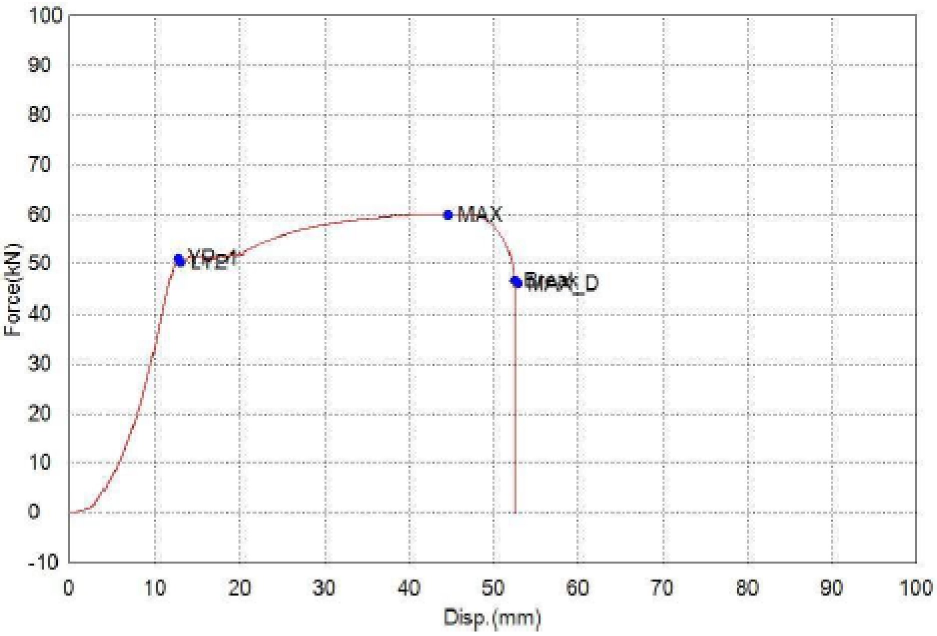


Figure B2 Tensile test result for 12 mm diameter

Key Word		Product Name	
Test File Name		Method File Name	Azim Rod 16mm.xmux
Report Date	1/31/2019	Test Date	1/31/2019
Test Mode	Single	Test Type	Tensile
Speed	10mm/min	Shape	Rod
No of Batches:	1	Qty/Batch:	1

Name	Diameter	LASE1_Force	YP(%FS)_Force	YS1_Force
Parameters		Stroke 1 mm	0.1 %	0.2 %
Unit	mm	kN	kN	kN
Azim Rod 3	16.0000	1.67885	119.973	-.-

Name	PointPicking1_Force	LYP_Force	Max_Disp_Force	Max_Force
Parameters				Calc. at Entire Areas
Unit	kN	kN	kN	kN
Azim Rod 3	-.-	118.392	105.200	137.363

Name	Break_Force
Parameters	Sensitivity: 10
Unit	kN
Azim Rod 3	106.400

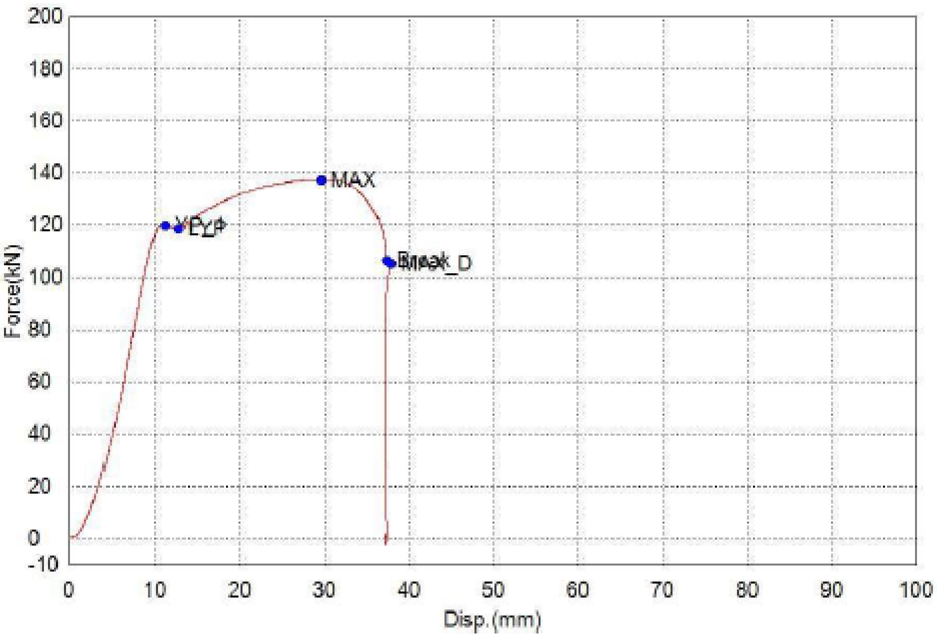


Figure B3 Tensile test result for 16 mm diameter

Appendix C Certificate of Calibration

KL Analytical Sdn Bhd (677718 K)

K-3-7, No. 2, Jalan Solaris
Solaris Mont' Kiara
50480 Kuala Lumpur, Malaysia
Tel : +603-6203 6083
Fax : +603-6203 6483
Email : info@klanalytical.com
Website :www.klanalytical.com

Certificate of Calibration

Number of page(s) 1/2

Certificate No. KLA/171031/SH01
Equipment Universal Testing Machine
Manufacturer Shimadzu
Model AG-300KNX **Serial No.** : I 33004600725
Capacity 300kN **Control No.** : M870501
Requested By UNIVERSITI TEKNOLOGI MALAYSIA(UTM)
UNIT PENGURUSAN MAKMAL UNIVERSITI KUALA LUMPUR,
JALAN SULTAN YAHYA PETRA,
54100 KUALA LUMPUR.
Calibration range 3 - 300kN
Resolution 0.01 **Indicator** : Digital
Calibration mode True Force
Date of Calibration 31 October, 2017 **Issue date** : 17 November, 2017
Calibration Due Date 30 October, 2019 (As request by customer)
Calibration location On Site
Condition of the item In Good Condition
Environments Temperature 23.5 ± 1.5 °C
Relative Humidity 57.5 ± 2.5 %

Calibration Method Reference ISO 7500-1 2015(E)

Reference Instrument	Serial No.	Certificate No.	Due Date
Load Cell With Digital Indicator 50kN	434892A	PSYP-17013503	10 March, 2018
Proving Ring, 300kN	5846	PSYP-16010675	20 December, 2017

Traceability This certificate is traceable to the International System of Unit which is maintained by the National Institute of Metrology

Calibrated by
Shahrum Bin Zakaria
Calibration Officer

KL Analytical Sdn Bhd (677718 K)

Approved by
Nicolas Ong
Quality Manager

Figure C1 Certificate of calibration for tensile machine (page 1)

K-3-7, No. 2, Jalan Solaris
Solaris Mont' Kiara
50480 Kuala Lumpur, Malaysia
Tel : +603-6203 6083
Fax : +603-6203 6483
Email : info@klanalytical.com
Website :www.klanalytical.com

KL Analytical Sdn Bhd (677718 K)

Certificate of Calibration

Number of page(s) 2/2

Certificate No. KLA/171031/SH01

Table 1 : Calibration results Compression

Reference Force (kN)	UUT Value (kN)	Error (%)	Relative Expanded Uncertainty (%)	k	Class of Machine
0	0	0	0.00	0	0
3.00	3.0007	0.02	0.24	2	0.5
9.00	8.9993	-0.01	0.24	2	0.5
15.00	15.003	0.02	0.24	2	0.5
24.00	24.014	0.06	0.24	2	0.5
30.00	29.983	-0.06	0.24	2	0.5
60.00	59.92	-0.13	0.24	2	0.5
120.00	119.75	-0.21	0.24	2	0.5
180.00	179.47	-0.29	0.24	2	0.5
240.00	239.65	-0.15	0.24	2	0.5
300.00	299.84	-0.05	0.24	2	0.5

Table 2 : The Characteristic values of the force measuring system

Reference force	(%) Relative error of				Relative Resolution
	Accuracy (*q*)	Repeatability (*b*)	Reversibility (*v*)	Zero (*f*o)	
-	-	-	-	-	-
3.000	0.0222	0.0167	-0.0111	0.0222	0.02
9.000	-0.0074	0.0056	0.0037	-0.0074	0.01
15.000	0.0178	0.0133	0.0178	0.0178	0.01
24.000	0.0583	0.0083	0.0167	0.0583	0.01
30.000	-0.0556	0.0067	-0.0156	-0.0556	0.01
60.000	-0.1333	0.0333	0.0334	-0.1333	0.02
120.000	-0.2056	0.0083	-0.0139	-0.2056	0.01
180.000	-0.2926	0.0056	-0.0149	-0.2926	0.01
240.000	-0.1472	0.0125	0.0111	-0.1472	0.00
300.000	-0.0522	0.0067	0.0145	-0.0522	0.00

* UUT - Unit Under Test

* The uncertainties are for a confidence probability of approximetely 95% and have a coverage factor k =2 unless stated otherwise

Figure C2 Certificate of calibration for tensile machine (page 2)

Machine Verification Certificate

ELE International

ELE House Order No.	214805
Customer's Name and Address: **MS INSTRUMENTS (SEA)** **52-2 JALAN USJ 9/5P** **UEP SUBANG JAYA** **46720 SELANGOR** **MALAYSIA**	

ELE International
Chartmoor Road
Chartwell Business Park
Leighton Buzzard
Beds. LU7 4WG England
phone: +44 (0) 1525 249200
fax: +44 (0) 1525 249249
email: ele@eleint.co.uk
http: www.ele.com

Machine Information	**ADR AUTO V2.0 3000BS EN COMPRESSION MACHINE**		
Compression Load Frame:	***36-4170/01***		
Capacity:	**3000KN**	Serial No:	**1890-1-1614**
Spherical Seating Serial Number:	**0974-14-3021**	Sell Center Lower Platen	**1857-2-2467**
Compression Load Frame:			
Capacity:	**250KN**	Serial No:	**1883-4-030**
Console Serial No:	**1913-3-0510**	Power Pack Serial No:	**1913-1-3213**

Load Indication Information:			
Confirm Test	9903A0036	Yes	
Digital ADR Touch Manufacturer's Serial No.		Serial No:	
Digital Readout Unit Calibrated	10 to 3000 kN	Serial No:	**1913-3-0510**
Hydraulic Pressure at Maximum Load	51 Mpa (7477 lbf/in^2)		

Verification	**This Certificate is valid for not more than 12 months**		
This testing machine was verified by reference to the proving device(s) as listed below. Before verification the testing machine was loaded three times to its maximum load capacity. The verification consister of three series of test loadings in general accordance with BS EN ISO 7500-1. The accuracy and repeatability errors of the machine have been calculated from the average of the three readings at each applied load and are shown overleaf.			
Serial No:	***1890-1-1614***	Range:	10 - 3000kN
Calibrated with reference to proving device serial number(s):			**25889 & 3000/3C**
Signed:	[signature]	Date:	**21/12/2015**
Name:	**W E RUFFLE**	For and on behalf of: **ELE International Ltd.**	

ELE International
Machine Verification Certificate 3000kN ADR-Auto and Manual Compression Machine
Form ELE-100
Issue 2, October 2013
1 of 2

Figure C3 Certificate of calibration for compression machine (page 1)

VERIFICATION RESULTS 1890-1-1614

Ambient temperature at the time of verification: 18.8 deg C

True Load Applied KN	Indicated Load			Mean	Error	Repeatability
	Test 1	Test 2	Test 3	Load	%	%
100	99.9	99.9	99.6	99.80	-0.20	0.30
150	149.9	150.2	149.8	149.97	-0.02	0.27
300	300.2	299.7	300.4	300.10	0.03	0.23
450	449.8	449.3	449.8	449.63	-0.08	0.11
600	600	600	600.4	600.13	0.02	0.07
1000	1002	1002	1001	1001.67	0.17	0.10
1500	1501	1501	1501	1501.00	0.07	0.00
2000	2003	2003	2003	2003.00	0.15	0.00
2500	2504	2501	2500	2501.67	0.07	0.16
3000	3000	2998	2998	2998.67	-0.04	0.07

Figure C4 Certificate of calibration for compression machine (page 2)

Appendix D Calculation for Bond Strength

Sample Calculation of Bond Strength

Given specimens: **G-150-10-3.5d-10%**

Parameters involved: Compressive strength, c/d ratio and embedment length

Compressive strength, *f'c*: 36.8 MPa (from same batch of pull-out specimens)

c/d ratio:

$$\frac{150-10}{2} = 45$$

$$\frac{45}{10} = 4.5$$

Embedment length, *L* :

$$3.5\ \times d = 35$$

Bond strength, τ_u :

$$\tau_u = \frac{P}{\pi d L}$$

Maximum load applied, *P* : 13.30361 kN

Area, πdL : π x 10 x 35 = 1099.557429 mm²

Bond strength, τ_u :

$$\frac{13.30361\ \times 10^3\ N}{1099.557429\ mm^2}$$

$$12.0990588\ \approx 12.10\ MPa$$

Sample Calculation of Bond Strength

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Bond strength, τ_u :

$$\frac{13.30361 \times 10^3\ N}{1099.557429\ mm^2}$$

$$12.0990588 \approx 12.10\ MPa$$

Normalised bond strength, τ_{norm}: :

$$\tau_{norm} = \frac{\tau_u}{\sqrt{f'_c}}$$

$$\frac{12.10}{\sqrt{36.8}}$$

1.99

LIST OF PUBLICATIONS

Indexed Conference Proceedings

1. **Sani, M. A**., Muhamad, R. & Mo, K. H. (2020). Effect of Ground Granulated Blast Furnace Slag as Partial Replacement in Fly Ash-Based Geopolymer Concrete. In *IOP Conference Series:Materials Science and Engineering*, 712, pp. 012002. IOP Publishing. http://doi.org/10.1088/1757-899X/712/1/01200.