FACULTY OF SCIENCE AND TECHNOLOGY

MASTER'S THESIS

Study programme / specialisation: **MSc. Petroleum Engineering/** **/Drilling and Well Engineering**	**Autumn semester, 2022 Open /** ~~Confidential~~
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Thesis title: **Determination of steel/cement friction coefficient**	
Credits (ECTS): **30 ECTS**	
Keywords: **Kinetic friction coefficient,** **confinement**	Pages: 109 + appendix: 26 Stavanger, *(31.01.2023)*

Abstract

Two different experimental approaches have been used to determine the kinetic coefficient of friction between carbon steel and concrete made of API class G well cement mixture.
First experimental setup consists of sliding steel plate, confined between concrete blocks of a sample while being pushed through them. Kinetic coefficient of friction was in this case calculated from the ratio of vertical load applied to push the plate downward to the normal force exerted perpendicularly and through the friction surface.
The second experimental setup was a conventional experiment of concrete block sliding on the inclined surface of steel plate. The angle that the incline makes with horizontal was used to determine the kinetic coefficient of friction in this case.
All the constructions necessary for experimental setup in both cases were designed and fabricated at the premises of University of Stavanger as a part of this research. Both experiments have been carried out on each of the six moulded cement samples. Results have shown that confinement results in much higher values of kinetic friction coefficient compared to unconfined sample sliding on an inclined plane.

Acknowledgements

First of all, I want to start by expressing my sincere gratitude to my supervising professor Jan Aage Aasen, who assisted and encouraged me from the very start to the finish of my work.
In addition, I would like to acknowledge the following individuals from University of Stavanger for their assistance: Jon Arve Andersen, Hans Joakim Skadsem, Kim Andre Nesse Vorland, Jostein Djuve, Foster Gomado, Emil Mannes Surnevik, Caroline Einvik and the rest of the team working at university workshop.
Finally, I would like to thank my family and friends, but especially my fiancée, who always stands by me during all the most difficult times and works alongside me to overcome any obstacles together.

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1. Introduction

1.1 Theory and methods

1.1.1 Conventional method of determining friction factor experimentally

In this section will be described one of the most applied methods for determining experimentally friction factor, also referred to as friction coefficient. This method was described in the 'Mechanics of Drilling' by Bernt S. Aadnoy. Equations from the book are based on the Coulomb friction model. According to this model, friction force is acting opposite in direction to the net force acting along the plane of contact and is directly proportional to the normal force.

Before the surfaces start slipping against each other, the maximum frictional force called static friction must be overcome. Static friction force (F) is related to normal force (N) by constant of proportionality called static friction coefficient (μ_S) as follows

Eq. 1: $F = \mu_S * N$

When two surface in contact with each other already start to slip, there exists kinetic friction force that is directly proportional to the normal force with constant of proportionality called kinetic friction coefficient (μ_K):

Eq. 2: $F = \mu_K * N$

Further in this research pairs of symbols (μ_S) and (mu_S) and symbols (μ_K) and (mu_K) will be used interchangeably but they are expressing the same things: static and kinetic friction coefficients respectively.

Coulomb friction model suggest that magnitude of friction force is independent of relative speed between slipping surfaces. Proportionality with normal force and the fact that this constant of proportionality depends on the characteristics of the surfaces in contact is called Amonton's second law of friction. Also, Amonton's first law of friction states that the size of the area of contact has no bearing.

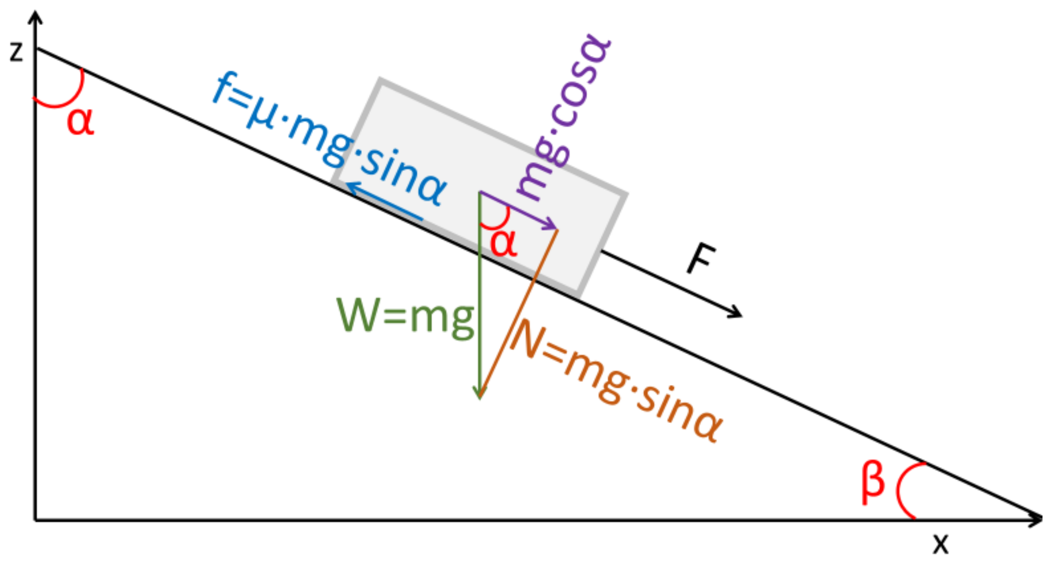


Figure 1: Forces acting on a body on an inclined plane

Conventional experimental setup for finding friction coefficient between block of concrete sample and inclined steel plate will be used as depictured on figure 1. Forces that are acting on the block are weight (W), normal force (N), friction force (f) and pulling force (F). When the force balance is set, then the pulling force F acting downwards along the plane can be described using following equation:

Eq. 3: $F = mg \cdot \cos\alpha - \mu \cdot mg \cdot \sin\alpha$

If the pulling force was acting in the upwards direction along the plane then it would be:

Eq. 4: $F = mg \cdot \cos\alpha + \mu \cdot mg \cdot \sin\alpha$

If pulling force from equation 3 is set to zero then force balance can be written as follows:

Eq. 5: $mg \cdot \cos\alpha = \mu \cdot mg \cdot \sin\alpha$

From this equation 5 friction coefficient can be defined as

Eq. 6: $\mu = \frac{mg \cdot \cos\alpha}{mg \cdot \sin\alpha} = \frac{1}{\frac{\sin\alpha}{\cos\alpha}} = \frac{1}{\tan\alpha}$ where α is an angle that inclined surface makes with vertical as shown on the figure 1

In this research an angle β was measured instead of α. Then angle α was found as follows:

Eq. 7: $\alpha = 90° - \beta$ where both angles are measured in degrees

Angle β can be found as follows:

Eq. 8: $\beta = \sin^{-1}\left(\frac{(vertical\ length)}{(inclined\ length)}\right)$

Therefore, friction coefficient can de determined from angle β.

To find static friction coefficient friction, inclined plate must be lowered to its minimum so that angle β becomes as small as possible. Then the block of concrete sample is placed on inclined plate closer to the highest side. After that inclined plate with sample is being lifted from one side so that angle β is increasing. Inclined plate is being lifted until the moment when the block starts to slide and then fixed. At this point component of the weight ($mg \cdot \cos\alpha$) that is parallel to the sliding surface just overcomes the static friction force ($\mu \cdot mg \cdot \sin\alpha$) therefore the sample starts to slide. In this position static friction coefficient can be found. First, vertical and inclined lengths of large triangle on figure 1 are measured. Then equation 8 can be used to find angle β. Then angle α from equation 7 can be calculated and this value inserted into equation 6 to find the static friction coefficient.

To find kinetic friction coefficient procedure is slightly different. Inclined plate this time must be lifted to its maximum height so that angle β becomes as large as possible. Then the block of concrete sample is placed on inclined plate closer to the highest side and released. Inclined plate is then being lowered while the sample is sliding down the plane, making angle β to decrease. If the sample gets to the bottom of the inclined plane, it is being lifted and released on the higher side of aninclined plane. Procedure is repeated until angle β becomes so small that kinetic friction force overcomes component of the weight ($mg \cdot \cos\alpha$) that is parallel to the sliding surface so the sample comes to a complete stop. Now the angle β can be used to find kinetic friction coefficient. First, vertical and inclined lengths of large triangle on figure 1 are measured. Then equation 8 can be used to find angle β. Then angle α from equation 7 can be calculated and this value inserted into equation 6 to find the kinetic friction coefficient.

1.1.2 Method of determining friction factor using pushout test on a confined plate

As a part of this research, alternative method of finding the friction coefficient has been proposed by the Author. This method includes a steel plate that is vertically confined between two blocks of concrete sample as shown on the figure 2.

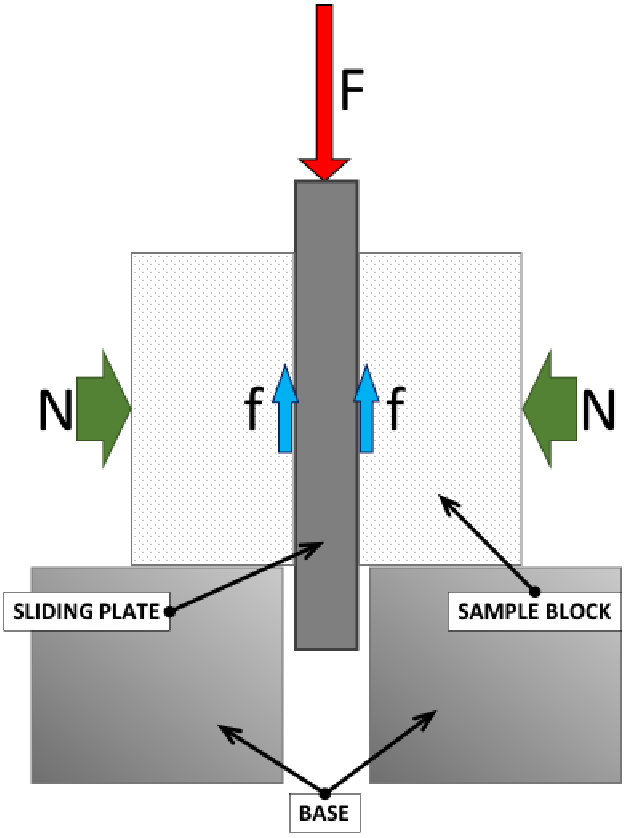


Figure 2: Force balance for the setup using pushout test on a sliding plate confined between concrete blocks of sample

Two concrete blocks of sample (further referred to as 'sample blocks') are resting on the base with the sliding steel plate positioned in between them. Base has an opening in the middle for the sliding plate so that plate's movement is not restricted when it's sliding downwards between both sample blocks. A construction further referred to as 'vice' applies the force N from the outer sides of sample blocks that are parallel to the contact surface between sliding plate. Force N, further referred to as 'normal force', compresses the sandwich of sliding plate and sample blocks together. Another force F, further referred to as 'vertical load' or simply 'load' is pushing on the sliding plate from above so that the sliding plate is getting displaced downwards between sample blocks. Interaction between surfaces of sample blocks and steel plate during pushout generates friction that acts in opposite direction to the vertical load. When the sliding plate is displaced with constant velocity, the vertical load (F) is balanced out by friction forces (f) on both contact surfaces:

Eq. 9: $F = f + f$

Therefore, friction force (f) can be expressed as:

Eq. 10: $f = \frac{1}{2}F$

According to coulomb law of friction, friction coefficient (μ) can be expressed as:

Eq. 11: $\mu = \frac{f}{N}$

By substituting expression for friction force (f) from equation 10 into equation 11, another expression for friction coefficient is found:

Eq. 12: $\mu = \frac{0.5 \cdot F}{N}$

Equation 12 is valid for both kinetic and static friction factors and can be determined from the ratio of vertical load to the normal force. As a part of this research only kinetic coefficient of friction was determined using this second method.

MTS Criterion C45 machine used in this research for displacing sliding plate with constant velocity has various settings and one of them is preload force that can be set to a specific value only. For this research preload value was chosen to be at 100N or 0.1kN. Data from the machine such as vertical load, displacement and elapsed time starts to be recorded as soon as the preload force of 0.1kN is reached. This means that the first measurements will be taken when the preset of 0.1kN is reached and not when the sliding plate just started to move. Another experimental setup must be used to determine static coefficient of friction using this method.

1.2 Hypothesis

Friction is the force generated when two surfaces in contact are moving relatively to each other or 'rubbing' on each other. Friction force is the force that opposes this relative motion. According to the Coulomb friction model, this force depends on the characteristics of two surfaces that are in contact with each other. Surface of any object, no matter how perfectly smooth it looks to a naked eye of observer, has some small irregularities, referred to as 'surface roughness'. As two surfaces are sliding between each other, those irregularities on their surface are interacting with each other, contributing to the friction.

In case with the first method, called 'Conventional method of determining friction factor', the sample is sliding on the surface of inclined plate. There are no external forces acting on that sample. Only weight and normal force perpendicular to the surface that is opposing weight. Sample is laying freely on the surface. It is not confined by any means from the top or from the sides. When the sample is sliding over the inclined surface, an interaction between upper surface of inclined plate in contact with bottom surface of sample takes place. Both surfaces have irregularities and sample has a freedom of movement to overcome these irregularities as it moves. An example can be a block sliding over the bump on the surface as depictured in figure 3. In the upper section is shown that

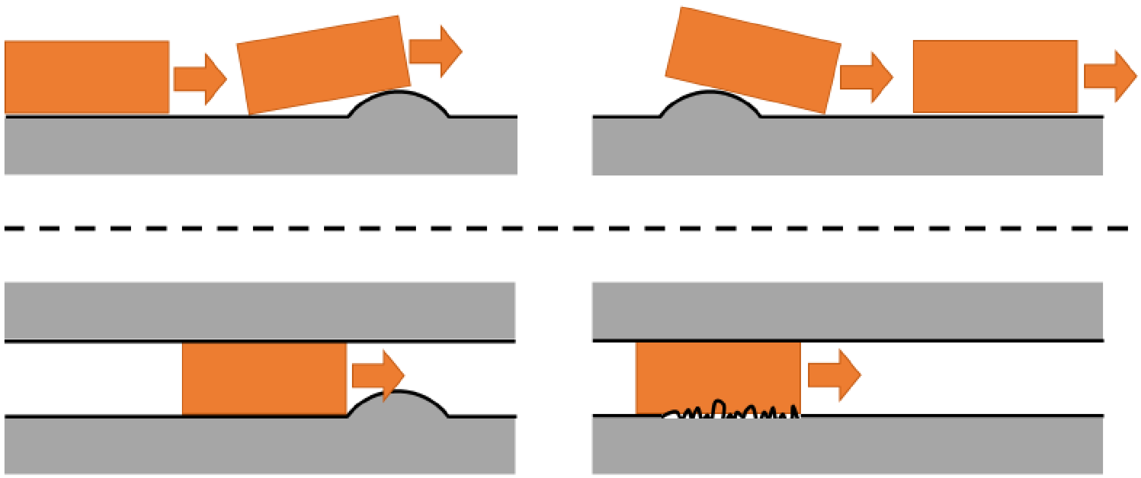


Figure 3: Block sliding over bump when not confined (upper figures) vs confined block crashing the bump as it slides through it

block that is not confined overcomes the bump just by sliding over it. At the bottom part of figure 3 is shown the block that is confined from above and below. In this case the block cannot just slide over the bump on the surface as it does not have enough of freedom in vertical movement. In this case for the block to pass the bump, the bump must be crushed by the block. In the last case more resistance is created for the block to slide.

The first situation on figure 3 represents what happens when the sample slides on inclined surface as in conventional method of determining friction factor. The second situation on figure 3 represents what happens when sliding plate confined between two blocks of sample is being displaced as in method of determining friction factor using pushout test.

Hypothesis is that confinement creates a higher friction coefficient compared to unconfined friction coefficient. This hypothesis is to be tested for kinetic coefficient of friction only by conducting conventional experiments and pushout experiments on confined sliding plate and comparing the results from both.

2. Design and manufacturing process of experimental equipment

This research has an experimental approach, so it heavily relies on preparation of experimental setup and testing. This section describes design and manufacturing process of constructions used in experiments that are part of this research

2.1 Modular construction for cement molding

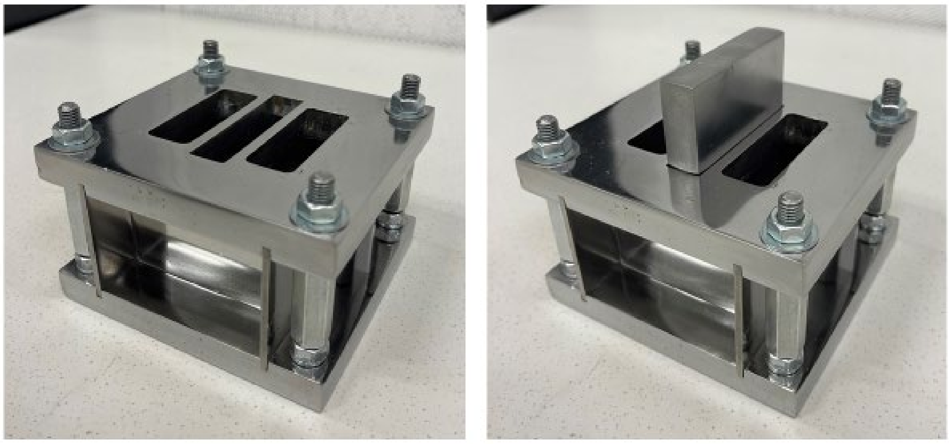


Figure 4: Modular molding construction with sliding plate (right side) and without (left side)

Modular molding construction (Figure 4) is the construction used to mold two cement blocks before they could be used in the pushout tests. This construction was designed by the author and produced at the workshop of the University of Stavanger. The design was developed considering the materials and machining equipment that was available at university at the time of manufacture. Construction resembles a rectangular box made of steel with two compartments separated by removable sliding plate in the middle. Construction is modular and consists of seven main parts or modules that are joined together and secured additionally by four metal threaded rods and nuts.

Main parts include:

- Top plate (Carbon steel)
- Bottom plate (Carbon steel)
- Sliding plate (Carbon steel)
- Two identical walls one in the front and one at the back (Stainless steel)
- Two identical walls one on the right and one on the left (Stainless steel)

Additional parts used in assembly of construction:

- Four M8 screw threaded rods of equal length (Carbon steel)
- Four M8 extension nuts (Carbon steel)
- Four standard M8 nuts (Carbon steel)
- Four M8 washers (Carbon steel)
- Four M8 spring washers (Stainless steel)

First, all the main elements were designed, and their respective 3D models were created using Autodesk Inventor Professional 2022 which is a 3D CAD software for designing 3D product prototypes. There were also created sketches for each part in Inventor software. Inventor uses an IPT File extension that contains sketches and features of the parts created. Wall at the front and back are completely identical to each other as well as the wall on the right and left. Therefore, one 3D model and sketch were made for each pair respectively.

Sketches created in Inventor include all the measurements and show the part from nine different angles: top, bottom, front, left, right, and side views at an angle from four different corners. Due to a very high resolution of the original sketch, most details are lost as the sketch is minimized to fit A4 format of the document. Therefore, additional figures have been created to represent information in a reader friendly format. Original Inventor sketches are still available in the appendix A.

Numbers in all sketches represent dimensions measured in millimeters. Numbers embedded in between the arrows pointing away from them are representing length of marked segment. Two numbers with an arrow pointing towards the circle are representing diameter and depth of the hole respectively.

Following Figures 5 – 9 are using information from original Inventor sketch (Figure 134 in the appendix A) to represent design and dimensions for the top plate in a reader friendly format. First Figure 5 provides only a visual representation of the top plate. This figure shows the top plate viewed at an angle from four different corners.

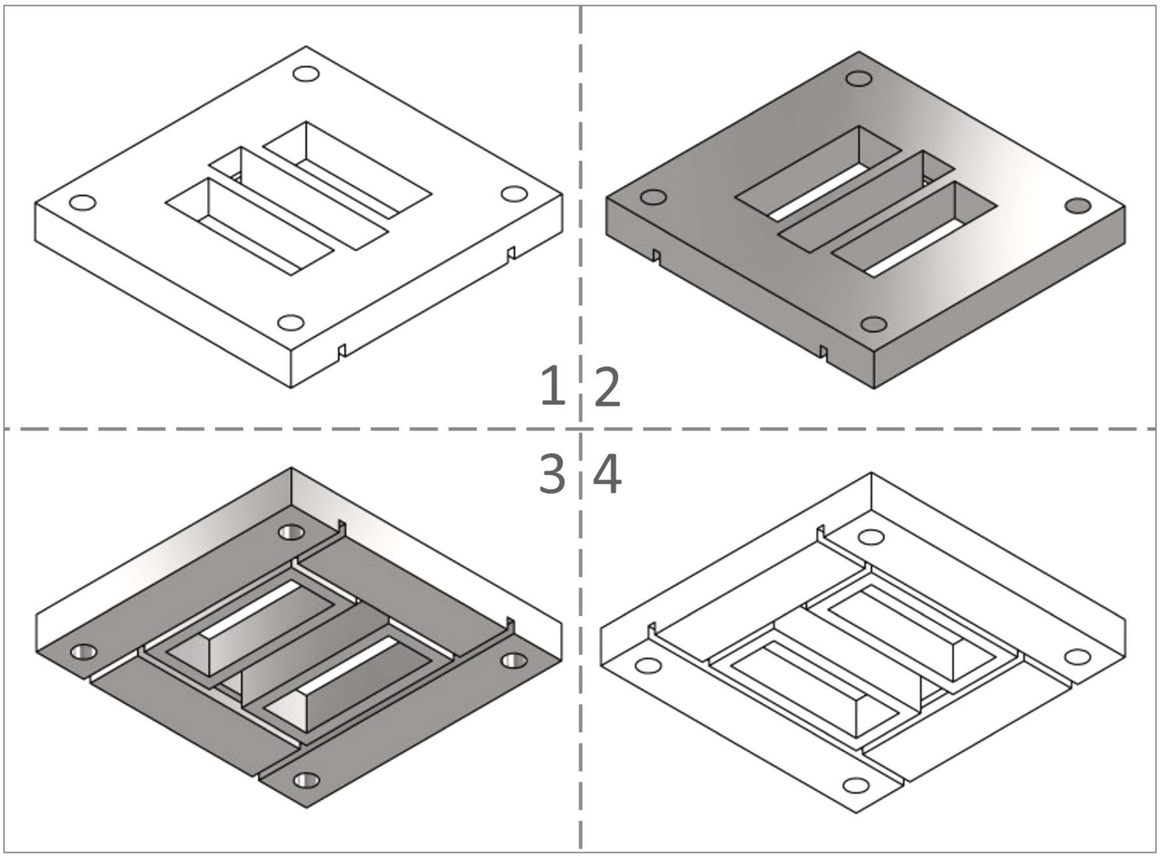


Figure 5: Sketch of the top plate viewed at four different angles

Information on the dimensions of the top plate is given on the following figures 6 – 9. Figure 6 shows the top plate viewed from above.

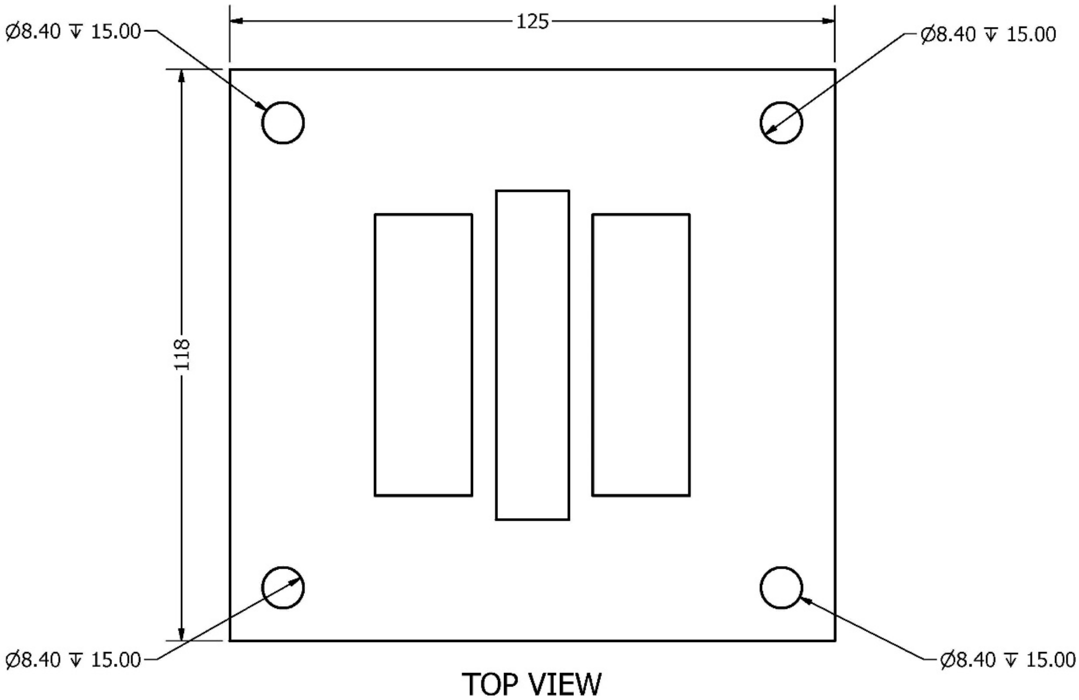


Figure 6: Sketch of the top plate viewed from above

Figure 7 shows the top plate viewed from below. Figure 8 shows the top plate viewed from the front side that is identical to the rear side. Figure 9 shows the top plate viewed from the left side that is identical to the right side.

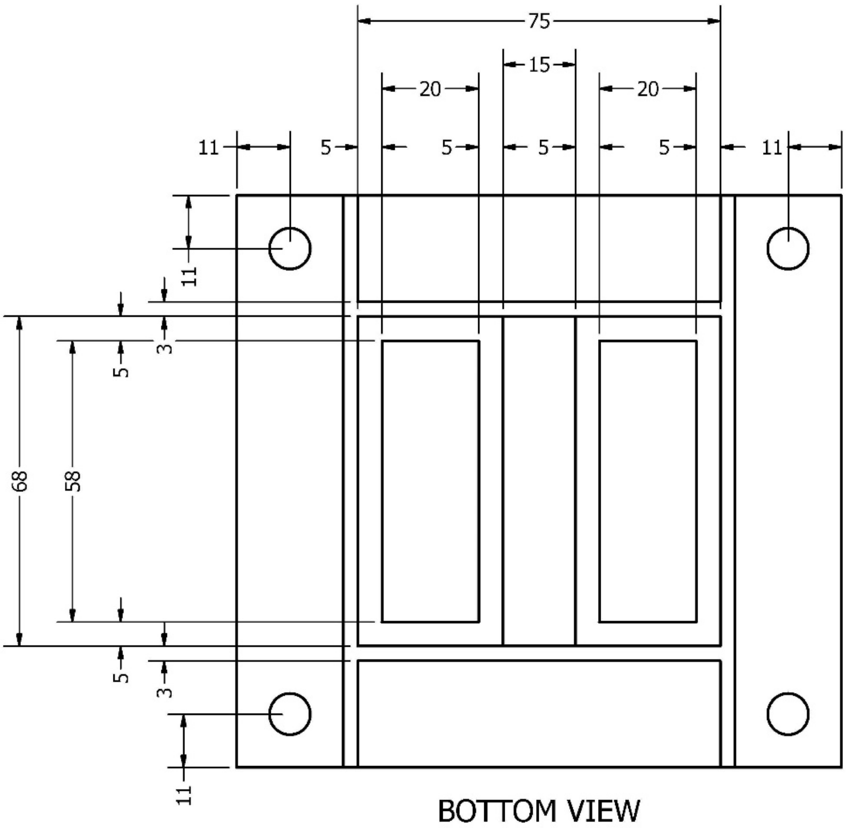


Figure 7: Sketch of the top plate viewed from below

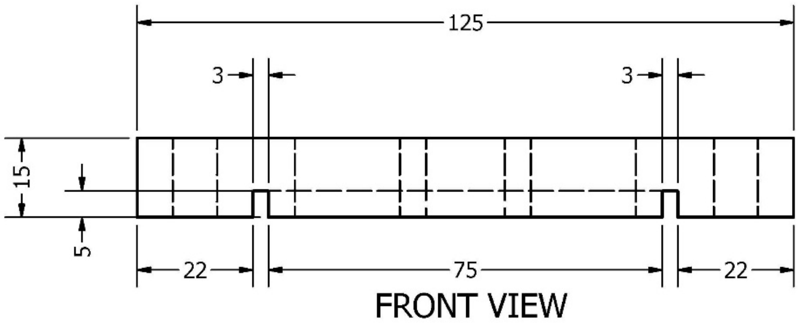


Figure 8: Sketch of the top plate viewed from the front side

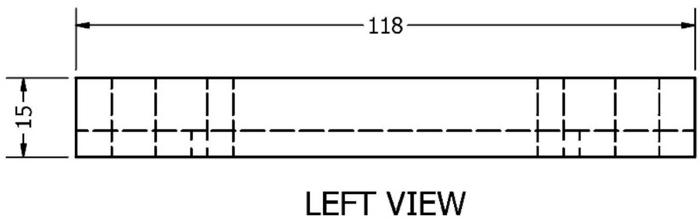


Figure 9: Sketch of the bottom plate viewed from the left side

Following Figures 10 – 14 are using information from Figure 135 in appendix A to represent design and dimensions for the bottom plate in a reader friendly format. First Figure 10 provides only a visual representation of the bottom plate. This figure shows the bottom plate viewed at an angle from four different corners.

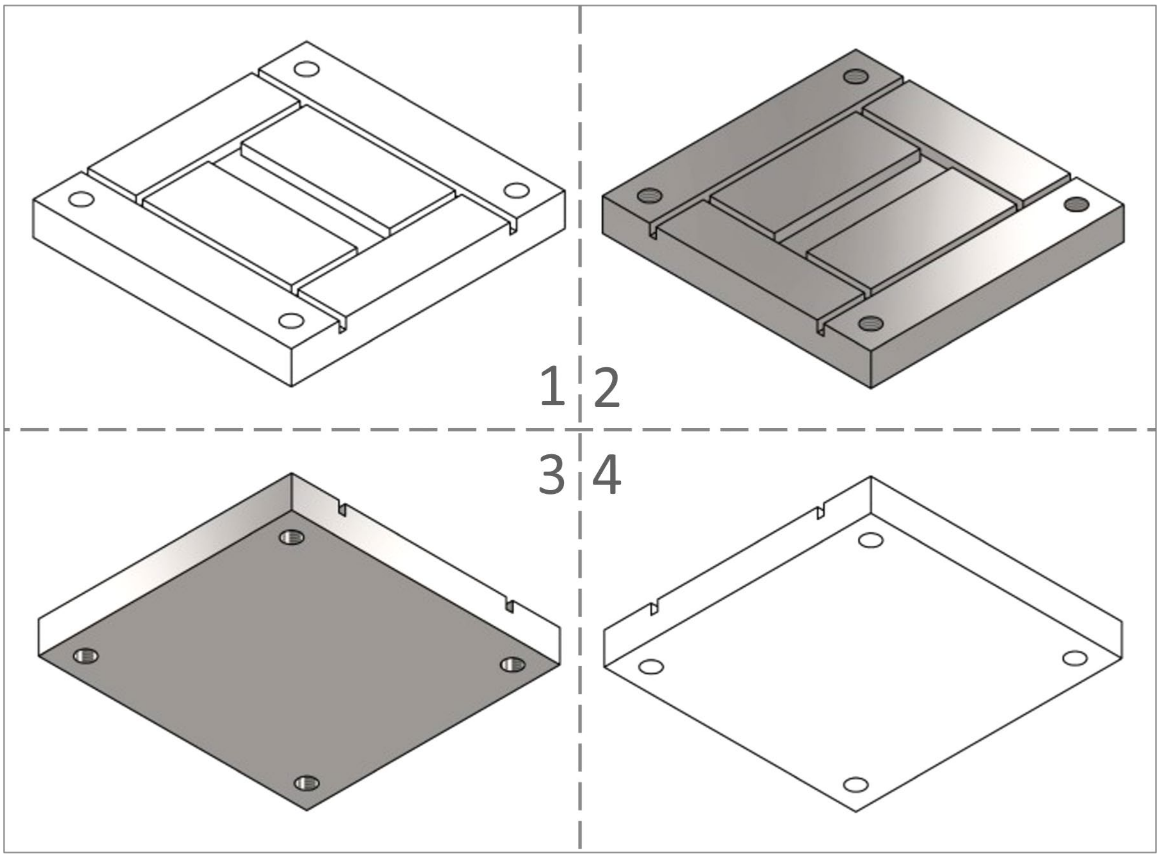


Figure 10: Sketch of the top plate viewed at four different angles

Information on the dimensions of the top plate is given on the following figures 11 – 14. Figure 11 shows the bottom plate viewed from the front side that is identical to the rear side. Figure 12 shows the bottom plate viewed from the left side that is identical to the right side.

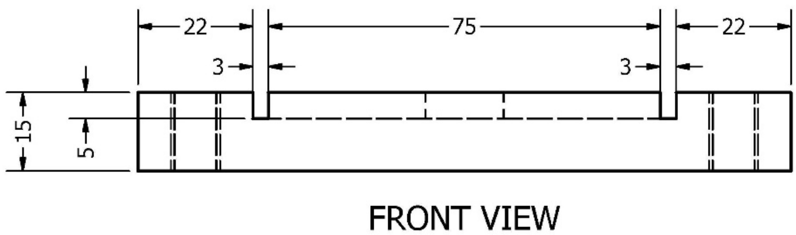


Figure 11: Sketch of the top plate viewed from the front side

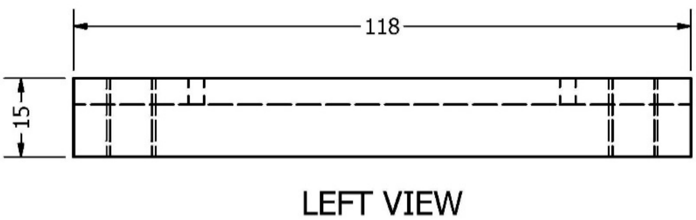


Figure 12: Sketch of the bottom plate viewed from the left side

Figure 13 shows the bottom plate viewed from above. Figure 14 shows the bottom plate viewed from below. Four holes at each corner of the bottom plate have M8 threads with thread pitch of 1.25 mm which is indicated on Figure 14.

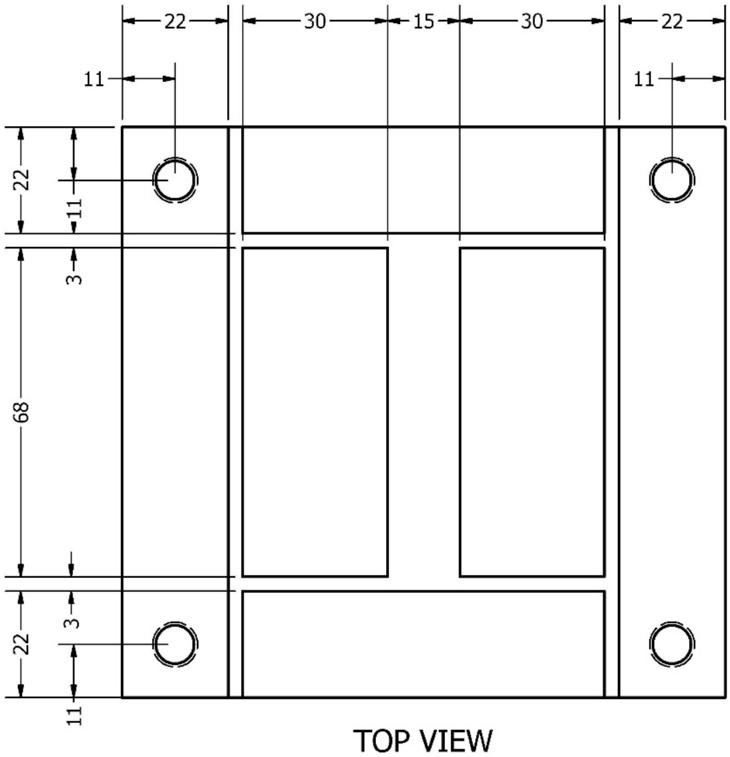


Figure 13: Sketch of the bottom plate viewed from above

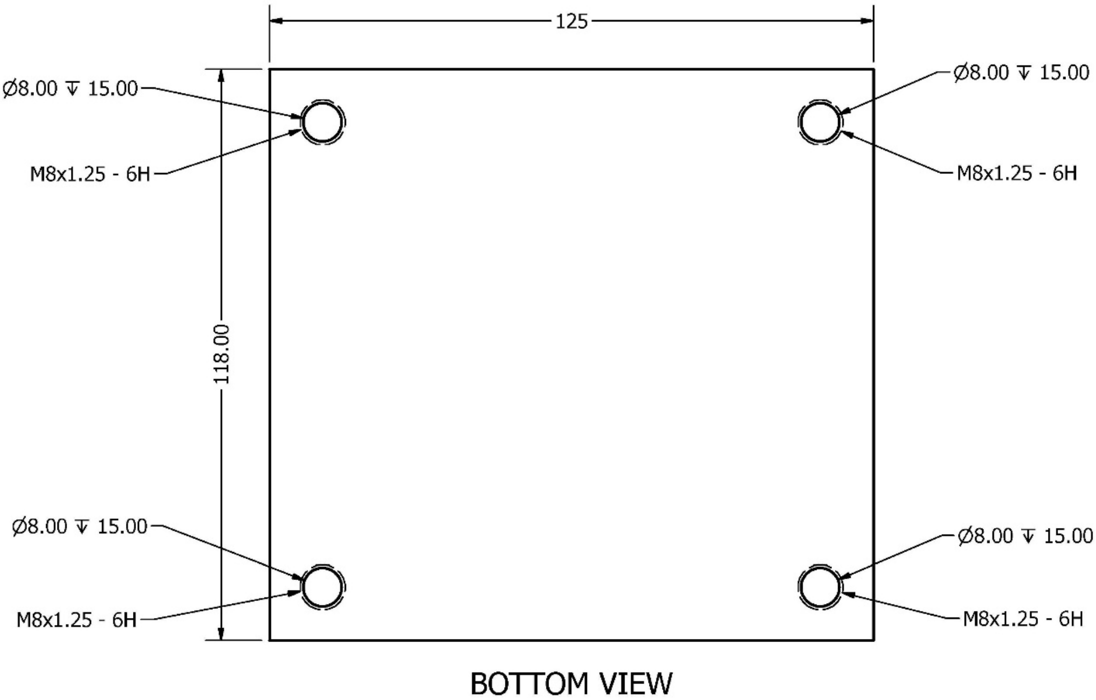


Figure 14: Sketch of the bottom plate viewed from below

Following three Figures 15 – 16 are using information from Figure 138 in the appendix A to represent design and dimensions for the sliding plate in a reader friendly format. This figure shows the sliding plate viewed at an angle from both corners.

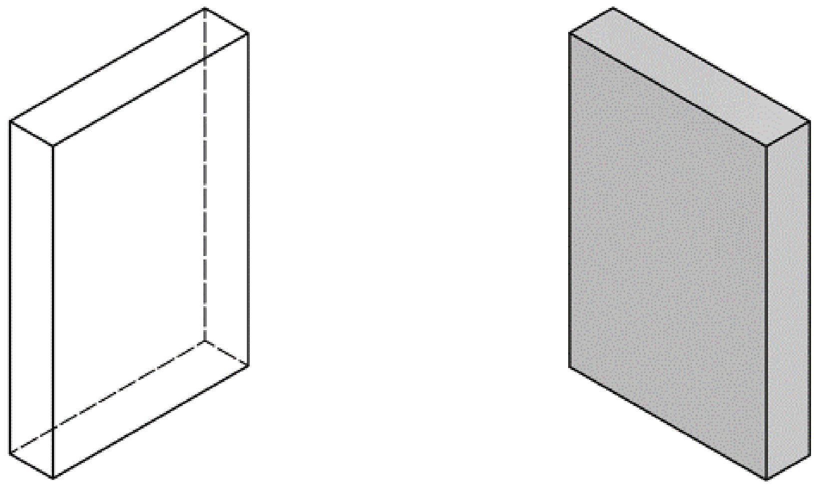


Figure 15: Sketch of the sliding plate viewed from two angles

Information on the dimensions of the sliding plate is combined on the figure 16. This figure shows the sliding plate viewed from the front side, left side and above. Front side is identical to the rear side, left side is identical to the right side and the top side is identical to the bottom one.

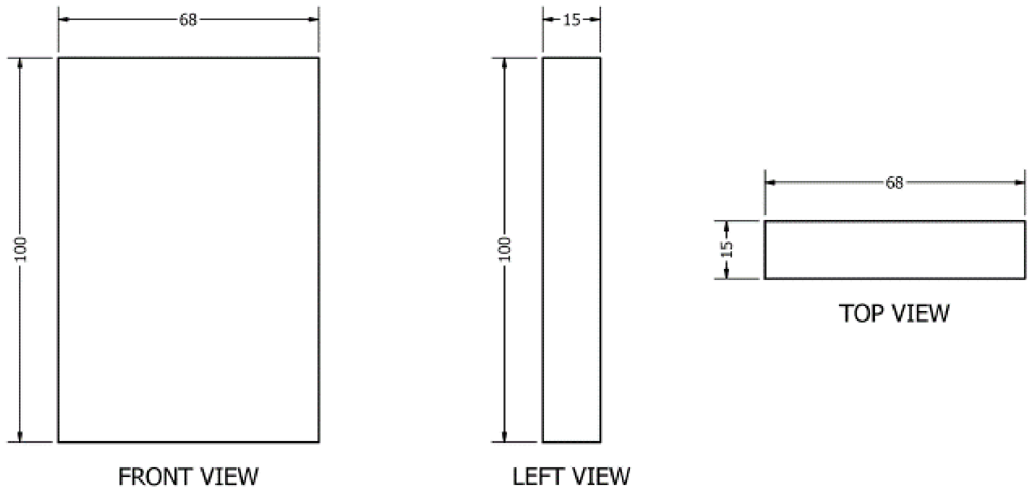


Figure 16: Sketch of the sliding plate viewed from the front, left and top side

Following three Figures 17 – 19 are using information from Figure 136 in the appendix A to represent design and dimensions for front and rear walls of construction in a reader friendly format. First Figure 17 provides only a visual representation of the front and rear wall that are completely identical to each other. This figure shows wall viewed from two different corners.

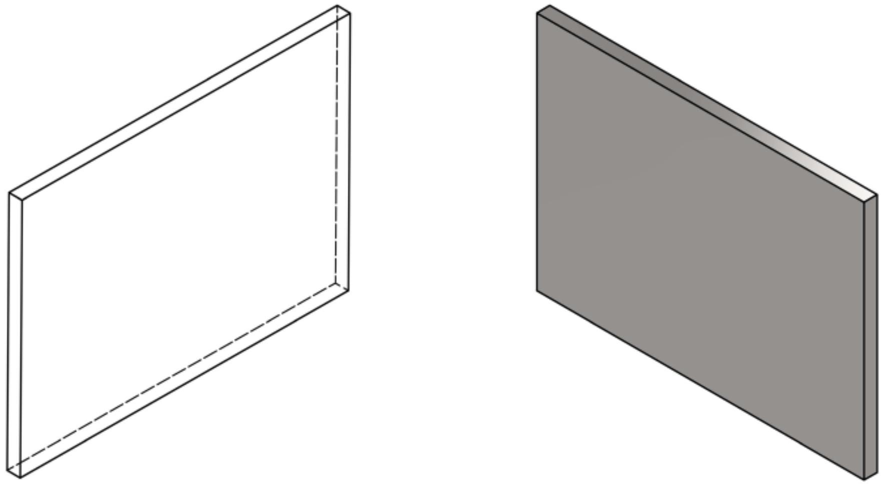


Figure 17: Sketch from two angles for the front and rear wall that are identical to each other

Information on the dimensions of the front and rear wall is combined on the figure 18 and figure 19. Figure 18 shows the wall viewed from the front and left side. Front side is completely identical to the rear side and left side is completely identical to the right side.

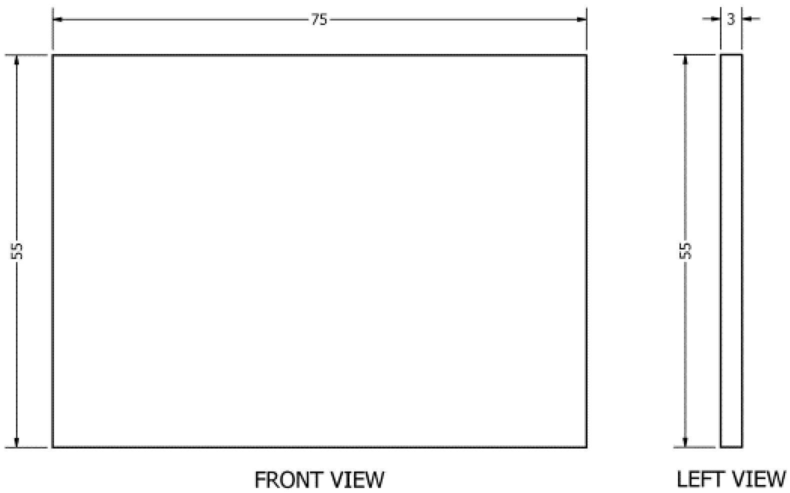


Figure 18: Sketch of the front and rear wall viewed from the front and left side respectively

Figure 19 shows the wall viewed from the top side which is completely identical to the bottom side.

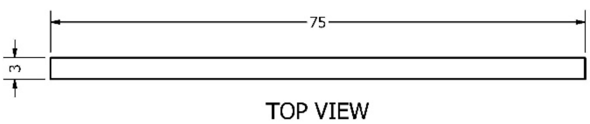


Figure 19: Sketch of the front and rear wall viewed from the top side

Following three Figures 20 – 22 are using information from Figure 137 in the appendix A to represent design and dimensions for the left and right wall of the construction in a reader friendly format. First Figure 20 provides only a visual representation of the left and right wall that are completely identical to each other. This figure shows wall viewed from two different corners.

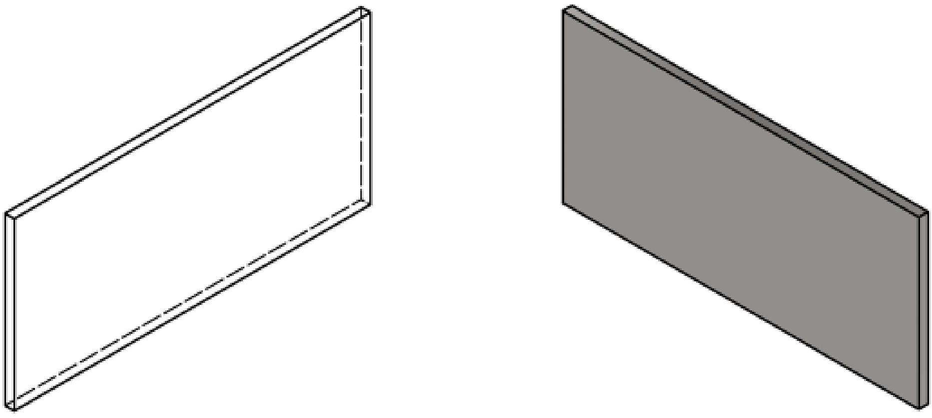


Figure 20: Sketch from two angles for the left and right wall that are identical to each other

Information on the dimensions of the left and right wall is combined on the figure 21 and figure 22. Figure 21 shows the wall viewed from the front and left side. Front side is completely identical to the rear side and left side is completely identical to the right side.

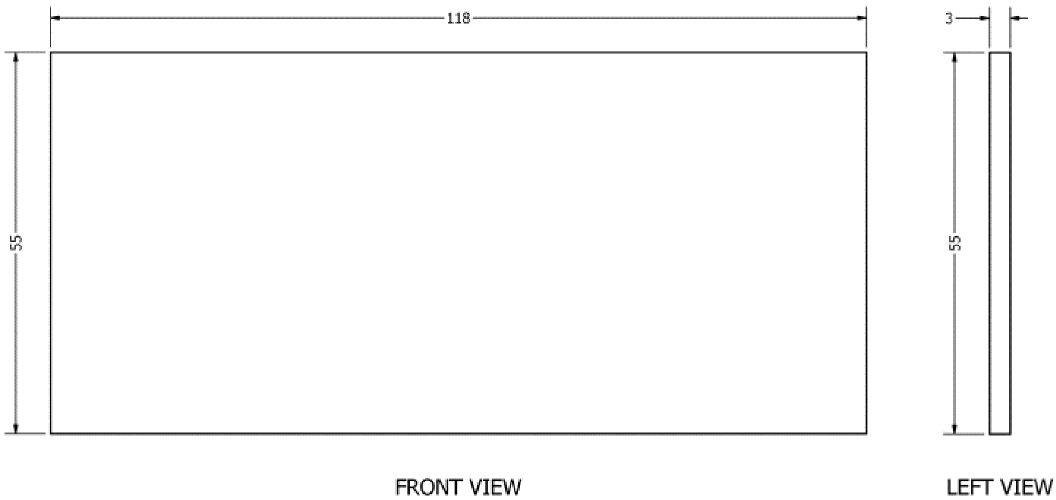


Figure 21: Sketch of the left and right wall viewed from the front and left side respectively

Figure 22 shows the wall viewed from the top side which is completely identical to the bottom side.

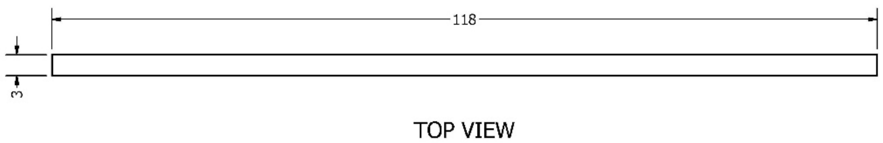


Figure 22: Sketch of the left and right wall viewed from the top side

After 3D models of main parts were created in Autodesk Inventor Professional 2022, manufacturing process can be started. Top and bottom plates for modular molding construction were machined using CNC (Computer Numerical Control) milling machine “Mazak Vertical Center Smart 430A” (Figure 23).

Figure 23: CNC milling machine Mazak

Only experienced person with the proper training is eligible to perform further procedures that include the usage of CNC milling machine. The author of this research lacks the necessary training for operation of CNC milling machines so the chief engineer at university workshop took over the further process of manufacturing top and bottom plates.

Autodesk Inventor IPT files containing 3D models of the top and bottom plates were opened in Inventor CAM (Computer Aided Manufacturing) software to create running toolpath of milling and drilling. After the running toolpath was programmed, it is then simulated in the software to check if there are any hiccups or collisions between tool or the tool holder and the component. If this is the case, then another milling path must be chosen. Also milling bits of proper size must be chosen. Bottom plate can be used as an example to show how important those simulations are. It has a rectangular opening in the middle, allocated for the sliding plate to fit through. Figure 24 shows a simulation where a milling bit of larger size is used. Larger bit is incapable of cutting deep enough into the corners which are left rounded instead of being straight. Then a bit of a smaller size is chosen so that the corners can be machined straight as construction requires.

When the simulation has passed the test with proper milling path, the file is then post processed to create a new ISO file. ISO file, also sometimes called NC file or G-code, is file containing commands for CNC machine on what to do. It consists of lines of code that are organized in blocks where each block is controlling cnc machining operation.

Figure 25 shows as an example part of the G – code used for manufacturing bottom plate. Each line in the code starts with a letter followed by a number. Any combination of these corresponds to specific type of action. For example, letter ‘G’ provides motion codes for the machine. ‘G1’ command governs the working feed rate. ‘S’ command sets the rotation speed for the bit. ‘S1019’ from figure 25 means that rotation speed of the bit is set to 1019RPM (rotations per minute).

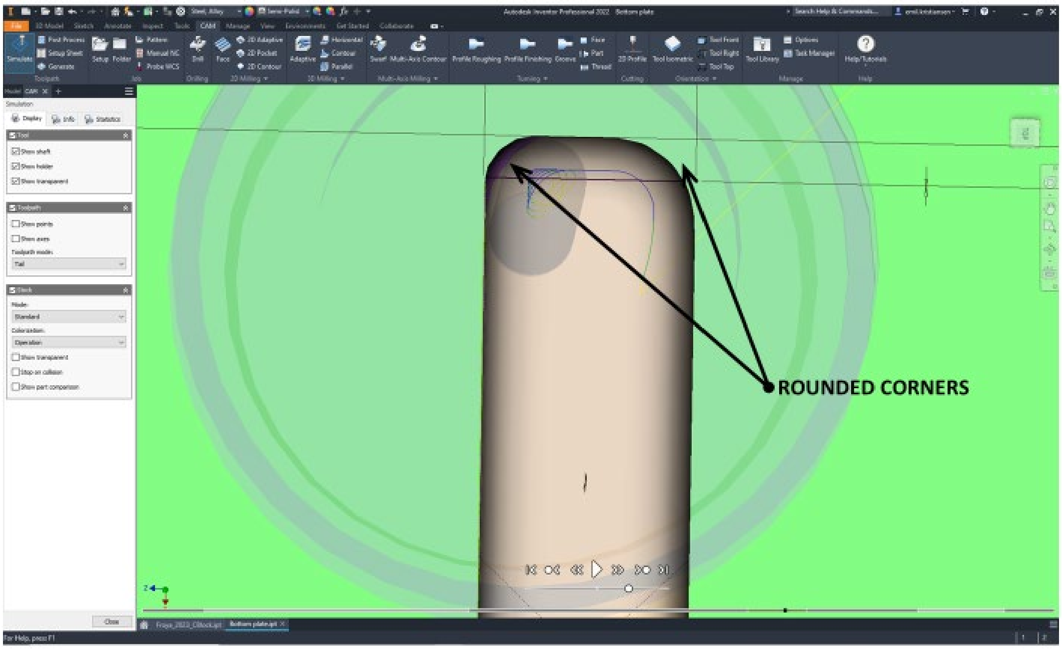


Figure 24: Running toolpath simulation in Autodesk Inventor CAM software revealing hiccup

```
O5238 (Modular stopeform bunn)
(T1 D=3. CR=0. - ZMIN=-6. - FLAT END MILL)
(T5 D=50. CR=0. - ZMIN=-1. - FACE MILL)
(T8 D=6. CR=0. - ZMIN=-5.99 - FLAT END MILL)
(T9 D=6.8 CR=0. TAPER=118DEG - ZMIN=-19.043 - DRILL)
(T12 D=12. CR=0. - ZMIN=-15.999 - FLAT END MILL)
(T20 D=20. CR=0. - ZMIN=-18. - FLAT END MILL)
G90 G94 G17
G21
G28 G91 Z0.
G90

(FACE1)
T5 M6
T20
S1019 M3
M8
G0 X167.5 Y4.262
G43 Z15. H0
G0 Z5.
G1 Z4. F100.
G18 G3 X162.5 Z-1. I-5. K0.
G1 X150.
X-20. F509.3
G17 G2 Y38.125 I0. J16.931
G1 X150.
G3 Y71.988 I0. J16.931
G1 X-20.
G2 Y105.85 I0. J16.931
G1 X150.
G18 G2 X155. Z4. I0. K5. F100.
G0 Z15.
```

Figure 25: Part of the G – code used for manufacturing of the bottom plate

ISO file is then transferred to USB flash drive and uploaded into CNC milling machine. Material for fabrication is secured inside the cabinet of CNC machine and the doors of the cabinet are closed tight. Now the manufacturing process can be initiated. No additional safety equipment is needed while operating the 'Mazak Vertical Center Smart 430A' CNC machine as manufacturing process is happening inside the sealed cabinet that has reinforced glass on the doors so the operator is well protected from any debris that can project during the manufacturing process. Nevertheless, operator must stay with the machine and have an overwatch until the manufacturing process is finished. ISO file contains the sequence of all commands and coordinates for the CNC machine and the process is fully automated. But CNC machine must be fine-tuned every time a new sample is used. Even though samples have the same composition, they still can have slightly distinct properties. Even though both samples for manufacture are cut from the same long carbon steel plate, their characteristics still might be slightly distinct. It is the task of operator to adjust the feeding speed and rotation speed as well as other parameters during the manufacturing process. It is a very delicate fine-tuning process that requires experience therefore this job was performed by experienced professional.

When top and bottom plates were readily fabricated their surfaces were looking rough with the traces from machining process as shown on figure 26.

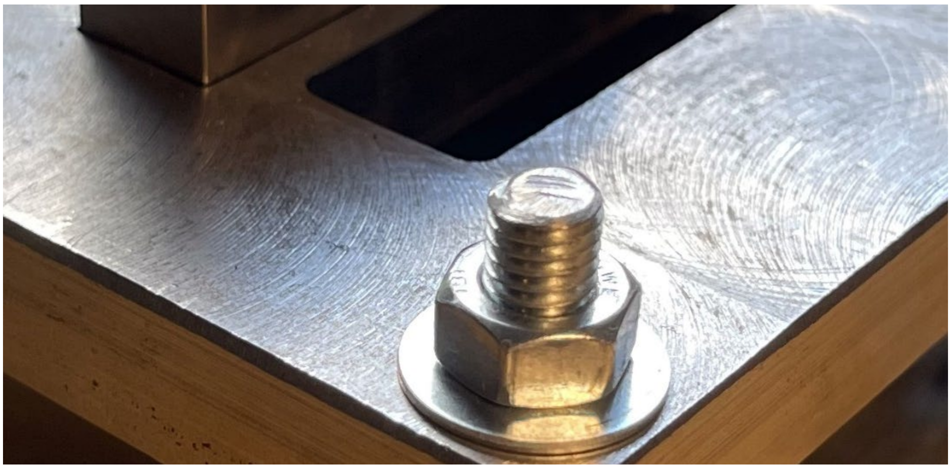


Figure 26: Freshly machined surface of the top plate out of CNC machine

Other main parts such as walls and sliding plate don't include complicated shapes such as grooves and rectangular holes. Therefore, CNC machine was not used for their manufacture. All four walls were cut from 3mm thick stainless steel metal plate using the metal sheet cutting machine (Figure 27). Four threaded rods with length of econd. 90mm were cut from a single long M8 threaded rod

Figure 27: Metal sheet cutting machine Strojarne Piesok NTV200/4

using an angle grinder. Sliding plate was cut from long carbon steel plate using horizontal metal cutting band saw machine (Figure 28). Then the surfaces of sliding plate were faced down using conventional milling machine Luna STF-5000V (Figure 29). This was done to remove the rusty layer as well as to make surfaces of plate perfectly smooth and parallel to each other. More details on the operation of milling machine are given in section 2.2.1.

Figure 28: Horizontal metal cutting band saw machine Rusch

Figure 29: Conventional milling machine Luna STF-5000V

Once all the main parts for modular molding construction were manufactured, they were then polished. Prior to polishing all the surfaces of the parts were sanded using sanding disks attached to orbital power sander machine (Figure 30). First, the sanding pad of K40 grit was used. Then pads of

Figure 30: Sanding and polishing equipment

K80, K120 and K240 were used on all surfaces of the parts respectively. The only exception is the sliding plate that was sanded with K40 sanding grit only. The higher is the number after letter ‘K’ the finer and less aggressive is the sanding pad. K40 is the roughest and most aggressive sanding pad among them while K240 is the finest one. More aggressive sanding pad bites deeper into the material leaving deeper grooves. Finer sanding pads are making the surface smoother, but they remove a tiny amount of material compared to aggressive ones. Pads are switched from aggressive to fine during sanding process to minimize the time of sanding. Sanding process was then finished off by using extra fine sanding paper K800 grit by hand.

Finally polishing can be done. For that purpose, microfiber polishing pad was attached to orbital power sander and ‘Autosol’ metal polishing paste was used to give a metal clean and shiny look. Now all main parts for assembling modular molding construction are ready (Figure 31).

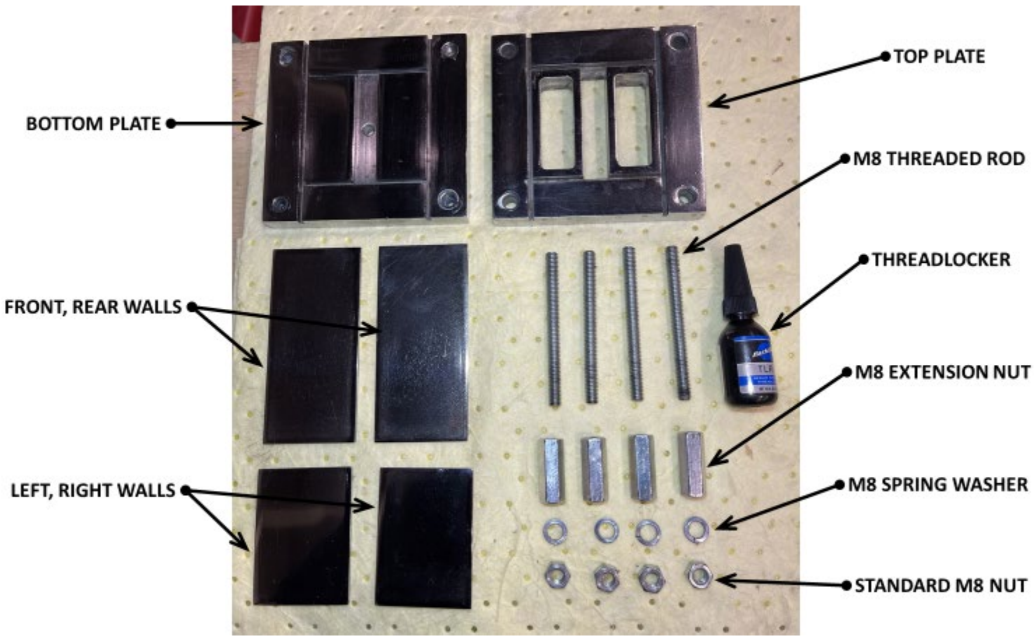


Figure 31: Parts for the assembly of modular molding construction

Assembly process is started by putting a drop of medium strength thread locker on to one end of 90mm threaded rod figure 32 – 1. Then this rod is screwed by hand into threaded hole at the corner

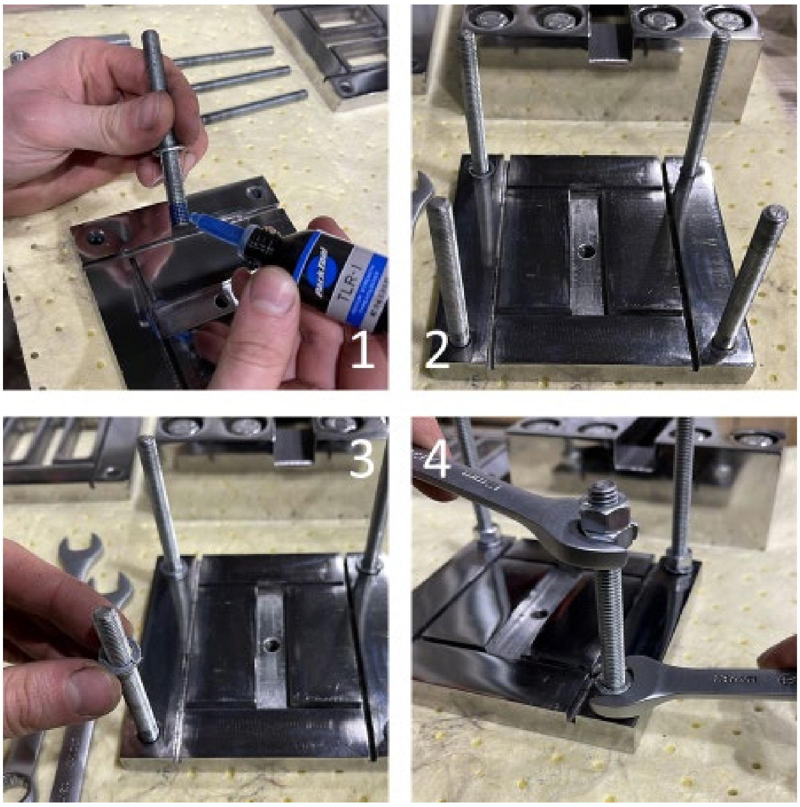


Figure 32: Mounting of threaded rods to the bottom plate

of bottom plate. Rod must be flush with the bottom surface of the plate so that it's sticking out only above the plate but not below. Process is repeated for each rod until all four of them are connected to the bottom plate as shown on figure 32 - 2. M8 spring washer is then moved over each threaded rod (Figure 32 – 3), followed by a standard M8 nut that is hand tightened at the base of the rod. Two M8 nuts are then tightened against each other at the upper end of the rod (Figure 32 – 4). 13mm wrench goes over those nuts to prevent threaded rod from spinning while the nut at the base is being tightened. Finally, M8 extension nuts are screwed on each rod until they meet the nut at the base (Figure 33).

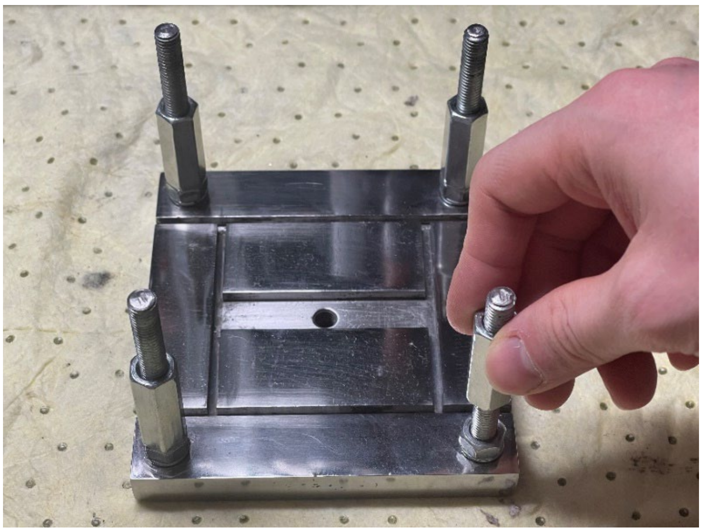


Figure 33: Mounting extension nuts

At this point, the fabrication of all the components for the modular molding structure is complete. The next step will be assembling them all together like pieces of puzzle to end up with the construction shown on the figure 4 in the beginning of this section. This further procedure is described in section 3.1.3.2 of this research.

This small section provides an overview of the courses author has taken to be able to use equipment and machinery at university premises in a safe way with accordance of HMS guidelines.

Name of the course: Nivå 0 HMS PÅ TekNat

HSE (health, safety and environment) course is an online course that provides an introduction to behaviour, rules and safety in the laboratories at the Faculty of Science and Technology at the University of Stavanger (UiS). Course is and must be taken each year before the start of the fall semester.

Name of the course: Nivå 1 TN-felles

Through this course, candidate learns about various risks and ways to safeguard oneself against them. Additionally covered are the proper lab behavior and some fundamental concepts regarding shared workspaces. The safe job analysis (SJA), reporting of undesirable situations, and what to do in the event of an accident are also covered.

Name of the course: Nivå 2 Maskin (Verkstedkurset)

Through this course, candidate is given a basic introduction of how to operate and maintain the most used machines in IMBM's (The Department of Mechanical and Structural Engineering and Materials Science at UiS) mechanical workshop. This introduction forms the foundation for further training on the machines to be used. Machinery reviewed during this course include:

- Lathe
- Milling machine
- Pillar bore
- Plate cutter
- Band saws
- Welding machine (MIG)
- Angle grinder
- Belt sander

Safe equipment during the use of university workshop includes safety goggles, clothes are not permitted to have any hanging ends that can be jammed inside the rotating machinery and shoes must be rigid and cannot have any open ends (like sandals) to minimize the injury if something heavy falls on the foot.

2.2 Construction for rectangular pushout tests

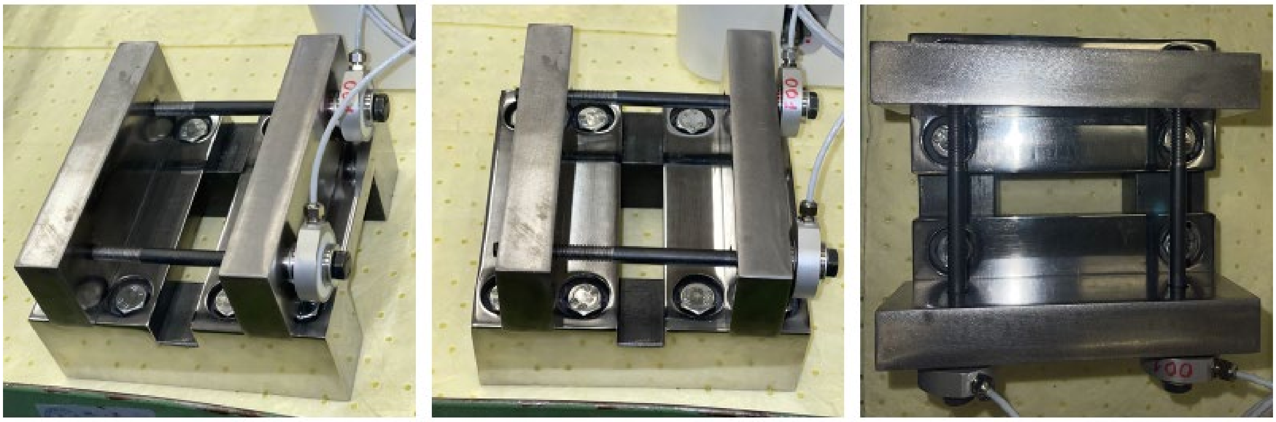


Figure 34: Rectangular pushout assembly construction viewed from three angles

Rectangular pushout construction is used in rectangular pushout tests that are the main focus of this research. This construction consists of two main parts that are resting one on the top of each other.

2.2.1 Lower part of construction or ‘Base’

The lower part of the rectangular pushout construction (Figure 35), further referred to as a ‘base’, acts as a support for the samples being tested. It also provides additional space for the sliding plate to be pushed through. Base resembles two upper bars slightly separated from each other, resting on two lower bars.

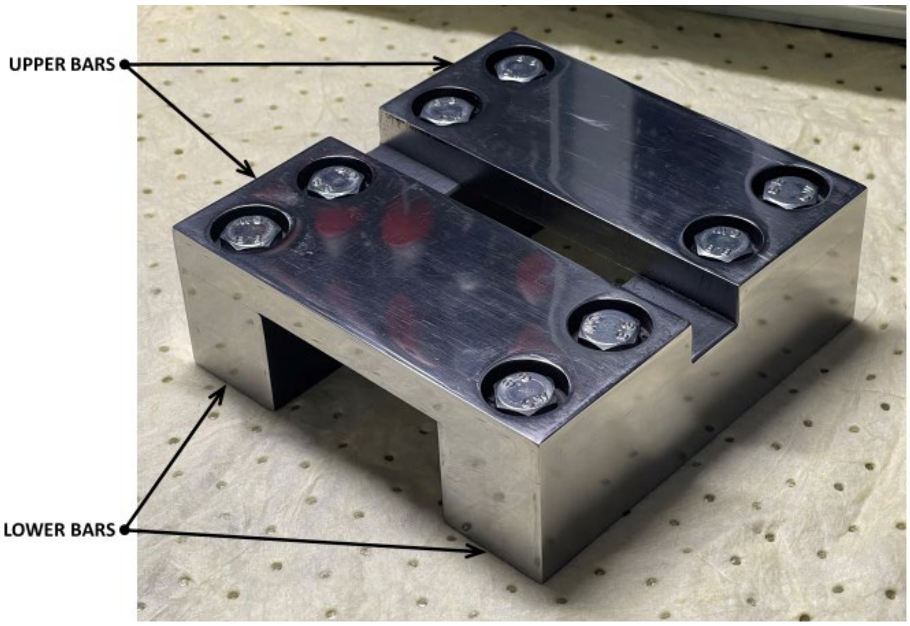


Figure 35: The ‘Base’ or the lower part of rectangular pushout construction

The upper part of the rectangular pushout construction (Figure 36), further referred to as a ‘Vice’, has the same function as the name suggests. It is used to compress the sliding plate in between two pieces of the concrete sample. It consists of two compression bars connected with long reinforced bolts on each side as shown on the figure 36.

The manufacturing process for both constructions was started from cutting solid rectangular steel bars (Figure 37) to desired length using horizontal metal cutting band saw (Figure 28).

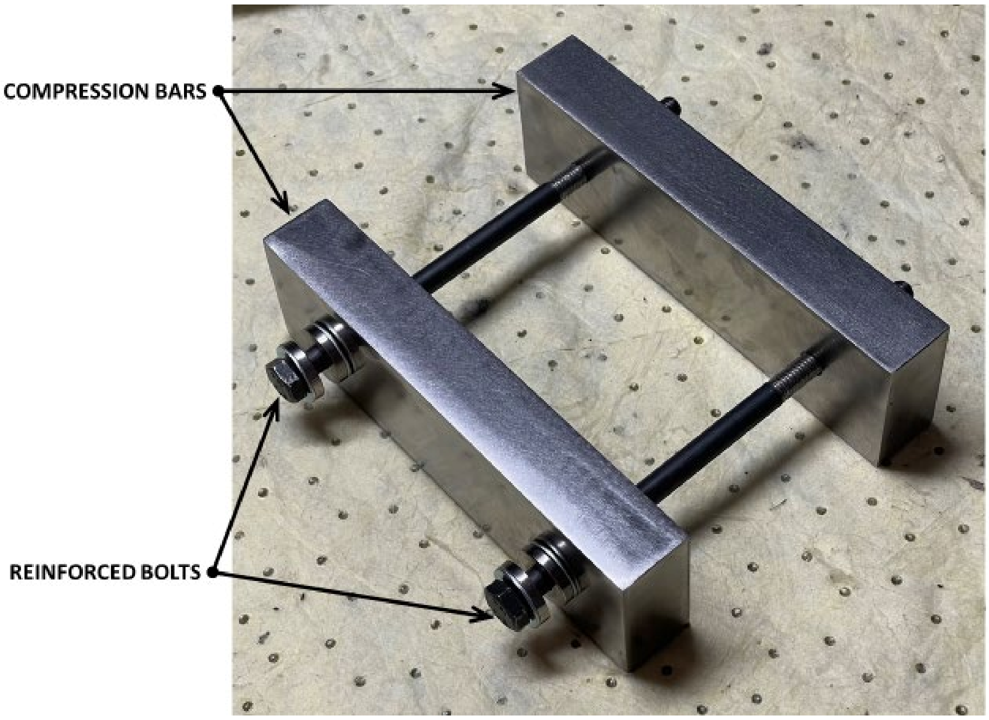


Figure 36: The 'Vice' or the upper part of rectangular pushout construction

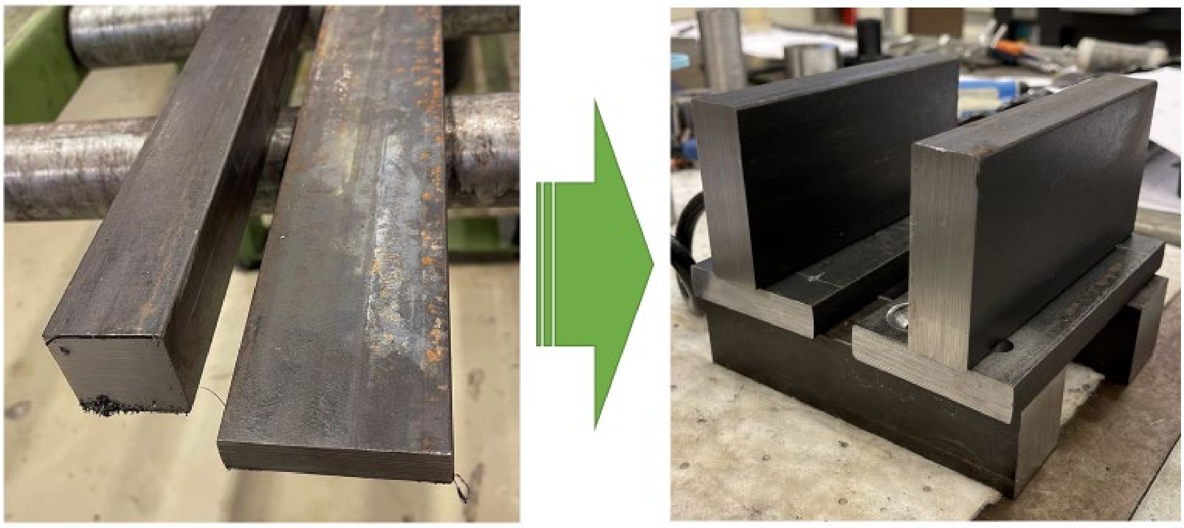
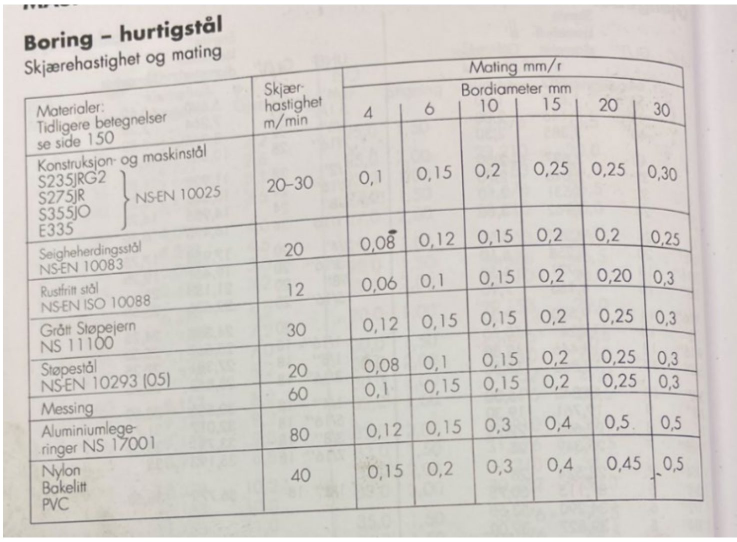


Figure 37: Sawing off solid rectangular steel bars to desired length

First, the manufacturing process of the 'base' will be described, and its dimensions will be provided in the end. Two segments of 160mm length were sawed off from 40x40mm solid steel bar. Those work pieces will be fabricated further to be turned into lower bars of the construction. Then two segments of 155mm length were sawed off another 70x15mm solid steel bar. Those ones will be turned into upper bars of the construction.

Upper bars are parallel to each other and are separated with 22mm gap as shown on figure35. Each of them is secured to the lower bars with four 40mm long M10 bolts. The correct rotation of the drill bit needs to be chosen using the workshop manual before 10mm holes can be drilled in each upper bar using the pillar bore Ibarmia AX-35 (Figure 40).

First the correct cutting speed [m/min] must be chosen from the table in figure 38. Drilling bits used are HSS steel and fabrication material to be drilled is a construction steel. The table in figure 38 gives then the cutting speed between 20 – 30 m/min. The diagram on the next figure 39 shows how to choose the correct RPM for the drilling operation. The left column is showing the diameter of



Boring – hurtigstål

Skjærehastighet og mating

Materialer: Tidligere betegnelser se side 150	Skjærhastighet m/min	Mating mm/r Bordiameter mm 4	6	10	15	20	30
Konstruksjon- og maskinstål S235JRG2, S275JR, S355JO, E335 } NS-EN 10025	20–30	0,1	0,15	0,2	0,25	0,25	0,30
Seigeherdingsstål NS-EN 10083	20	0,08	0,12	0,15	0,2	0,2	0,25
Rustfritt stål NS-EN ISO 10088	12	0,06	0,1	0,15	0,2	0,20	0,3
Grått Støpejern NS 11100	30	0,12	0,15	0,15	0,2	0,25	0,3
Støpestål NS-EN 10293 (05)	20	0,08	0,1	0,15	0,2	0,25	0,3
Messing	60	0,1	0,15	0,15	0,2	0,25	0,3
Aluminiumlegeringer NS 17001	80	0,12	0,15	0,3	0,4	0,5	0,5
Nylon Bakelitt PVC	40	0,15	0,2	0,3	0,4	0,45	0,5

Figure 38: Drilling with HSS (High Speed Steel) bit, cutting speed and feed

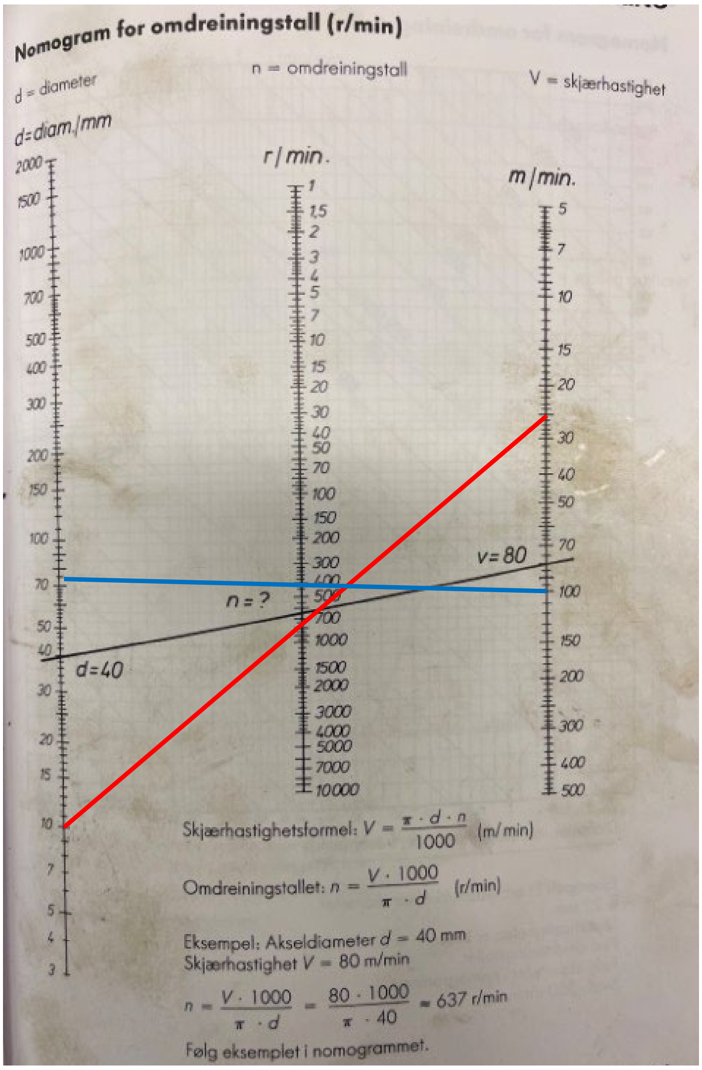


Figure 39: Nomogram for RPM

the drilling bit that is 10mm in this case. Column on the right is showing the values for the cutting speed. A value of 25m/min has been chosen. Then the red line is drawn in between those two points. Middle column is showing the values for RPM and the red line is crossing it at the mark of around 700RPM. Pillar bore has several fixed RPM speeds it can operate at. The closest one is at 692RPM (Figure 40) and this is the starting speed that needs to be chosen.

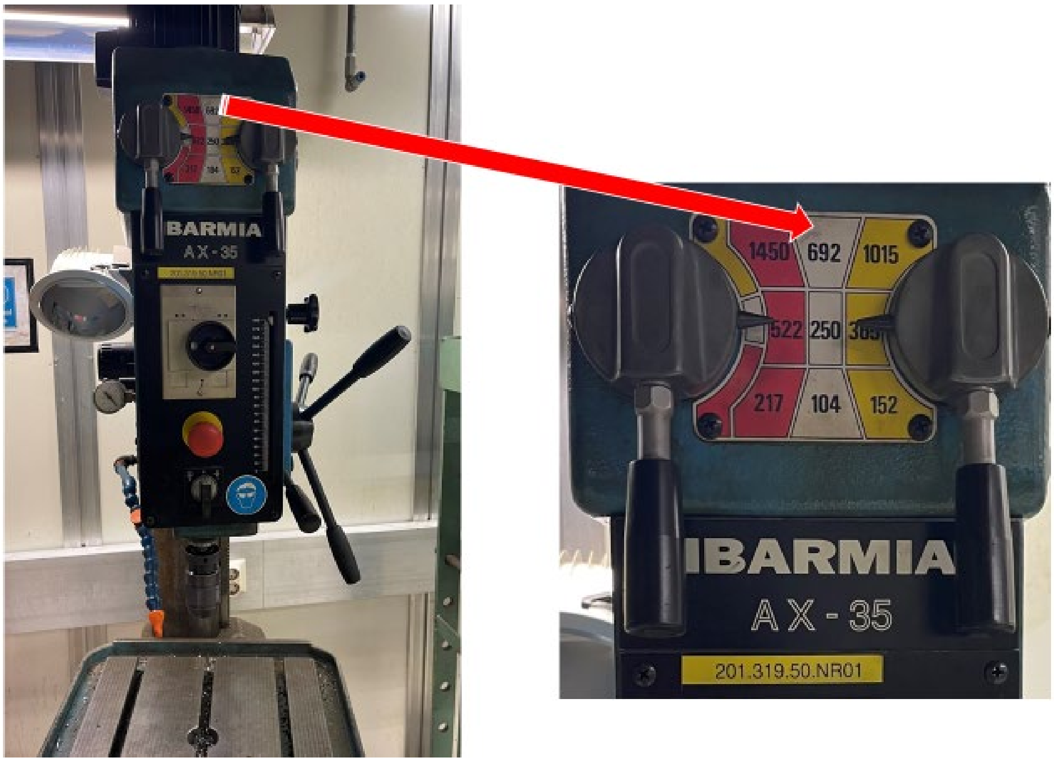


Figure 40: Rpm available for Ibarmia AX – 35 pillar bore

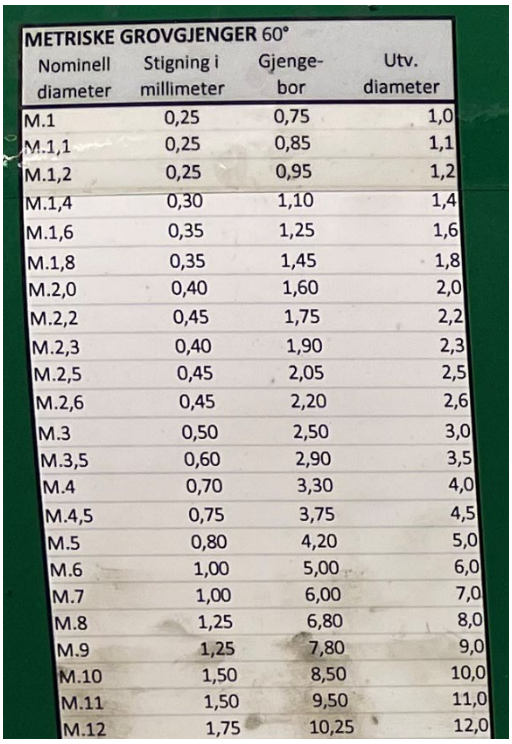
It is worth noting that workshop manual only gives estimate of the RPM that should be used initially as a guideline. There are many factors as material properties of particular steel used or the wear of the bit that may come into play. So, the RPM may be fine-tuned later during the process. Cutting oil is being used on the drilling bit to preserve it during the drilling and increase the drilling efficiency.

As seen on the figure 35, hex heads of the bolts are located slightly below the level of a workpieces surface. To achieve that, 10mm holes in upper plates were counterbored to create a cylindrical flat-bottomed hole 24mm in diameter and 8mm deep on the top of already predrilled 10mm holes. The diameter of the hole was chosen to be 24mm so that it can accommodate 17mm hex socket that later will be used to wrench the bolts in. Figure 41 shows the picture where the process of counterboring was performed by an Author using conventional milling machine from figure 29.

Table for the metric coarse threads at the workshop (Figure 42) was used to identify the correct diameter of the holes to be drilled in lower bars. Those holes will be threaded with M10 threads. From the figure 42 correct diameter of the hole for M10 threads is 8,5mm. Now four matching holes of 8,5mm in diameter were drilled in each lower bar.

Three M10 taper taps of different aggressiveness were then used to make threads in newly drilled holes. The first tap to be run into hole is the least aggressive. The last run was made with most aggressive tap. During the threading process a cutting oil was used to make threads smoother and threading process easier.

Figure 41: Counterboring process performed by an Author using conventional milling machine

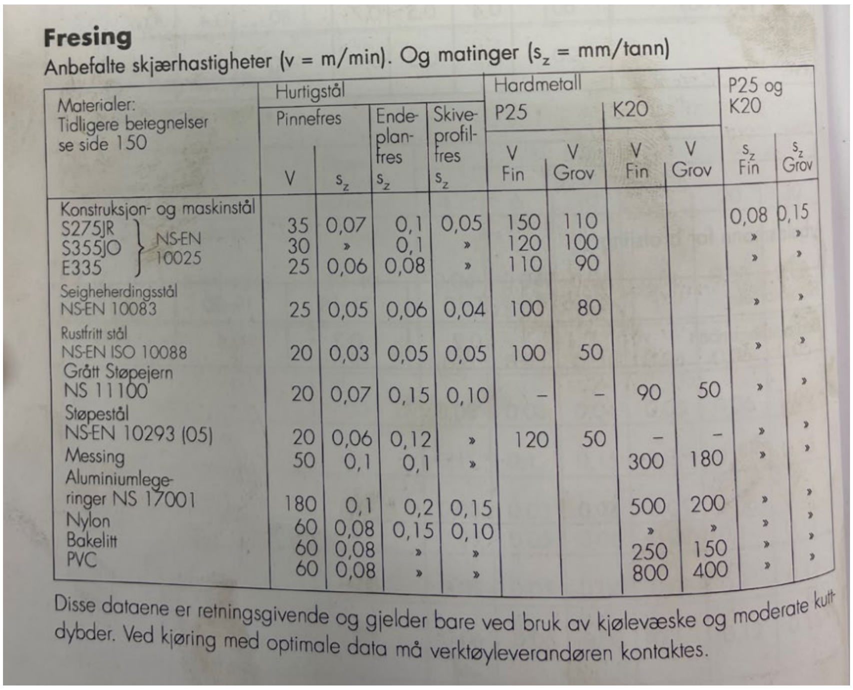


METRISKE GROVGJENGER 60°

Nominell diameter	Stigning i millimeter	Gjenge-bor	Utv. diameter
M.1	0,25	0,75	1,0
M.1,1	0,25	0,85	1,1
M.1,2	0,25	0,95	1,2
M.1,4	0,30	1,10	1,4
M.1,6	0,35	1,25	1,6
M.1,8	0,35	1,45	1,8
M.2,0	0,40	1,60	2,0
M.2,2	0,45	1,75	2,2
M.2,3	0,40	1,90	2,3
M.2,5	0,45	2,05	2,5
M.2,6	0,45	2,20	2,6
M.3	0,50	2,50	3,0
M.3,5	0,60	2,90	3,5
M.4	0,70	3,30	4,0
M.4,5	0,75	3,75	4,5
M.5	0,80	4,20	5,0
M.6	1,00	5,00	6,0
M.7	1,00	6,00	7,0
M.8	1,25	6,80	8,0
M.9	1,25	7,80	9,0
M.10	1,50	8,50	10,0
M.11	1,50	9,50	11,0
M.12	1,75	10,25	12,0

Figure 42: The table for the metric coarse threads

Now was the time for the facing process to begin. This process was executed using the facing bit on the milling machine. The similar procedures as for the drilling must be followed for the facing process. Table from figure 43 was used to determine recommended cutting speed for this milling operation. Milling bit is a hard metal type and fabricated material is construction steel.



Fresing

Anbefalte skjærhastigheter (v = m/min). Og matinger (s_z = mm/tann)

Materialer: Tidligere betegnelser se side 150	Hurtigstål Pinnefres V	Hurtigstål Pinnefres s_z	Hurtigstål Endeplanfres s_z	Hurtigstål Skiveprofilfres s_z	Hardmetall P25 V Fin	Hardmetall P25 V Grov	Hardmetall K20 V Fin	Hardmetall K20 V Grov	P25 og K20 s_z Fin	P25 og K20 s_z Grov
Konstruksjon- og maskinstål										
S275JR (NS-EN 10025)	35	0,07	0,1	0,05	150	110			0,08	0,15
S355JO (NS-EN 10025)	30	»	0,1	»	120	100			»	»
E335 (NS-EN 10025)	25	0,06	0,08	»	110	90			»	»
Seigheherdingsstål NS-EN 10083	25	0,05	0,06	0,04	100	80			»	»
Rustfritt stål NS-EN ISO 10088	20	0,03	0,05	0,05	100	50			»	»
Grått Støpejern NS 11100	20	0,07	0,15	0,10	–	–	90	50	»	»
Støpestål NS-EN 10293 (05)	20	0,06	0,12	»	120	50	–	–	»	»
Messing	50	0,1	0,1	»			300	180	»	»
Aluminiumlegeringer NS 17001	180	0,1	0,2	0,15			500	200	»	»
Nylon	60	0,08	0,15	0,10			»	»	»	»
Bakelitt	60	0,08	»	»			250	150	»	»
PVC	60	0,08	»	»			800	400	»	»

Disse dataene er retningsgivende og gjelder bare ved bruk av kjølevæske og moderate kuttdybder. Ved kjøring med optimale data må verktøyleverandøren kontaktes.

Figure 43: Recommended cutting speed and feed for milling

Cutting speed of 100 m/min is chosen. Milling bit has diameter of 75mm. Using this information, the blue line was drawn on the diagram in figure 39 and RPM for the milling operation is estimated at 400RPM.

Largest surfaces of upper bars have been faced first. This process is visualized on figure 44.

Figure 44: Facing process performed on the largest surface of upper bar

Then each upper bar was secured to the lower bars with four M10 bolts using a ratchet with 17mm socket. Now assembled construction resembles the base from figure 35. Then all the side faces of the construction have been faced as well as the bottom of the construction. During the facing process the layer of rust is removed making surfaces clean and shiny but most importantly all the faces of the construction become perfectly plain and aligned to each other at a straight angle. Finally, construction has been sanded and polished in the same manner as described for the modular molding construction. Following figure is showing an overview of all the parts making up the base.

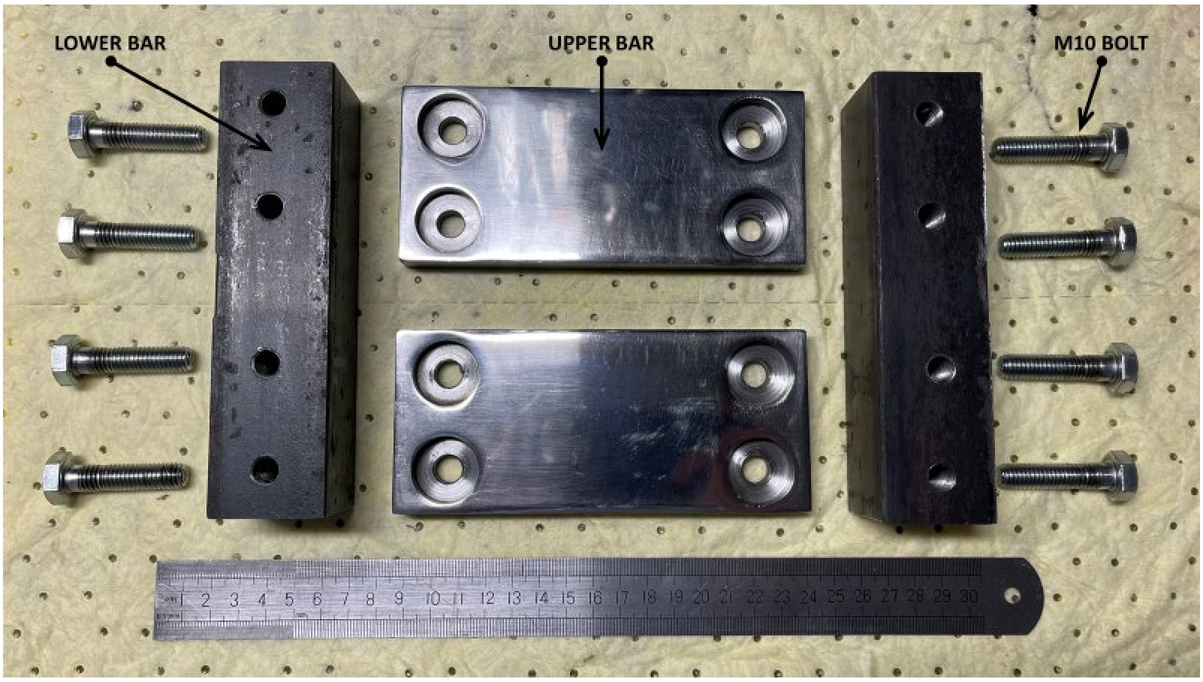


Figure 45: Collection of the parts that are making up the base

Figure 46 shows dimensions of upper bar. Figure 47 shows dimensions of the lower bar. Figure 48 shows overall dimensions of assembled base. ‘W’ stands for width, ‘L’ for length and ‘H’ for height. All the measurements are given in millimeters.

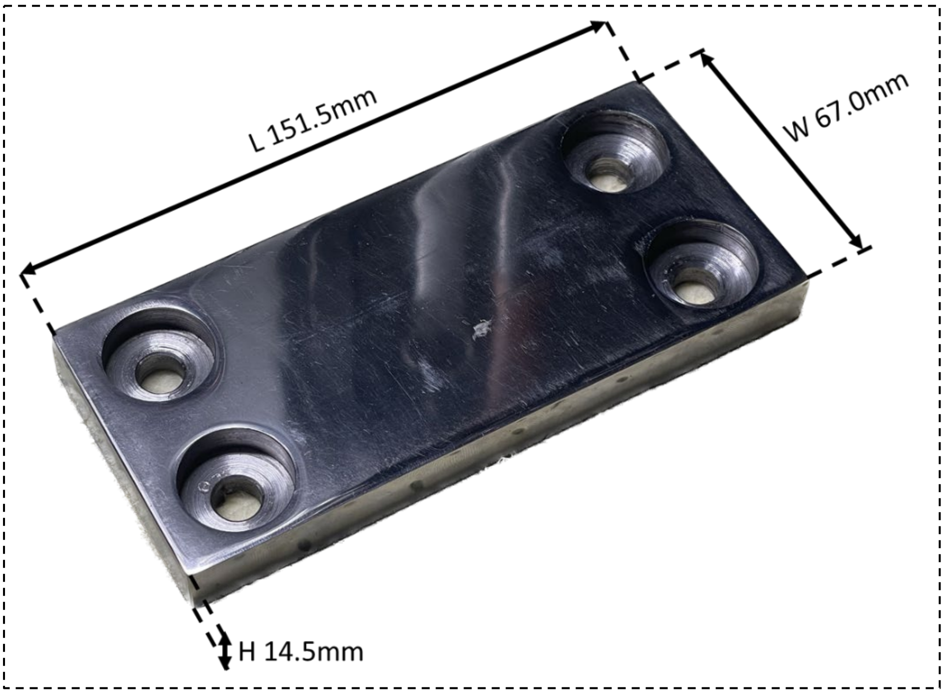


Figure 46: Dimensions of the upper bar

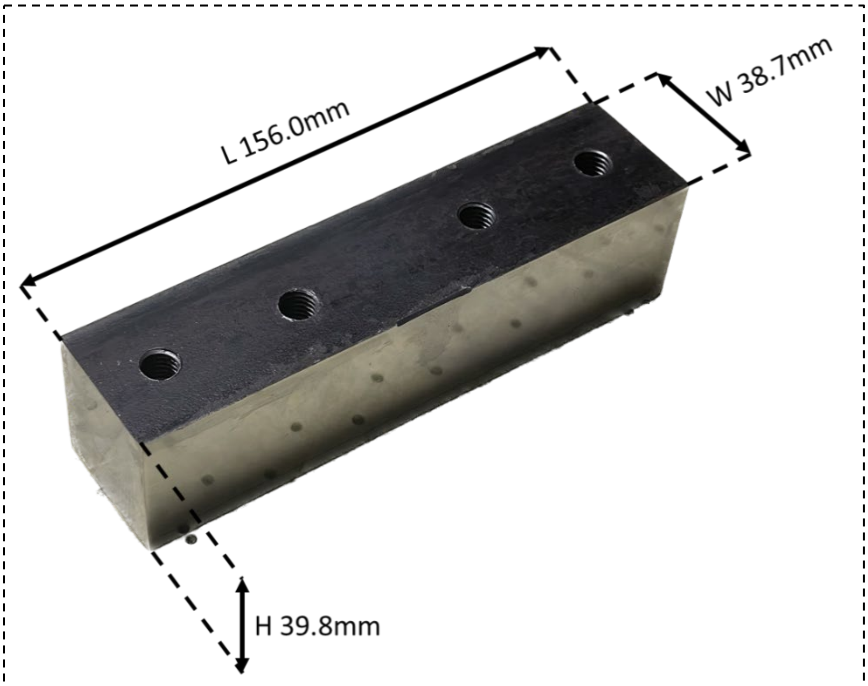


Figure 47: Dimensions of the lower bar

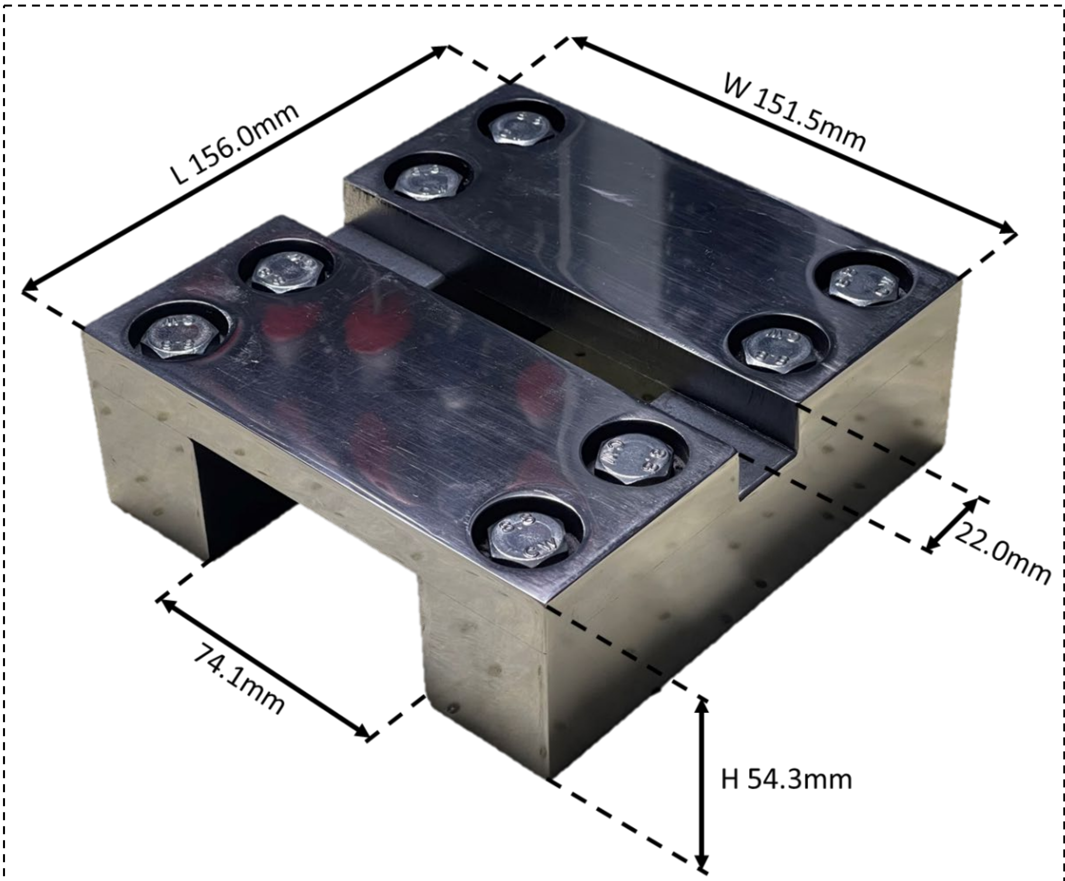


Figure 48: Dimensions of assembled base

2.2.2 Upper part of construction or 'Vice'

Now will be described the manufacturing process of the upper part of rectangular pushout construction, also referred to as 'vice' in this research. As mentioned earlier it consist of two compression bars and reinforced bolts pressing those together (Figure 36). Bolts are 150mm long M8 with 1.25mm thread pitch, reinforced with a strength grade of 10.9. This information was used to find physical properties of the bolts from the catalogue provided by producer. Table in the figure 49 shows that minimum breaking force of these bolts is 38.8kN.

Nominell gäng-diameter mm	Delning mm	Nominell spännings-area mm^2	Hållfasthetsklass 3.6	4.6	4.8	5.6	5.8	6.8	8.8	9.8	10.9
			Min. brottkraft ($A_s \cdot R_m$), N								
3	0,5	5,03	1 660	2 010	2 110	2 510	2 620	3 020	4 020	4 530	5 230
3,5	0,6	6,78	2 240	2 710	2 850	3 390	3 530	4 070	5 420	6 100	7 050
4	0,7	8,78	2 900	3 510	3 690	4 390	4 570	5 270	7 020	7 900	9 130
5	0,8	14,2	4 690	5 680	5 960	7 100	7 380	8 520	11 350	12 800	14 800
6	1	20,1	6 630	8 040	8 440	10 000	10 400	12 100	16 100	18 100	20 900
7	1	28,9	9 540	11 600	12 100	14 400	15 000	17 300	23 100	26 000	30 100
8	1,25	36,6	12 100	14 600	15 400	18 300	19 000	22 000	29 200	32 900	38 100
10	1,5	58,0	19 100	23 200	24 400	29 000	30 200	34 800	46 400	52 200	60 300
12	1,75	84,3	27 800	33 700	35 400	42 200	43 800	50 600	67 400'	75 900	87 700
14	2	115	38 000	46 000	48 300	57 500	59 800	69 000	92 000'	104 000	120 000
16	2	157	51 800	62 800	65 900	78 500	81 600	94 000	125 000'	141.000	163 000
18	2,5	192	63 400	76 800	80 600	96 000	99 800	115 000	159 000	–	200 000
20	2,5	245	80 800	98 000	103 000	122 000	127 000	147 000	203 000	–	255 000
22	2,5	303	100 000	121 000	127 000	152 000	158 000	182 000	252 000	–	315 000
24	3	353	116 000	141 000	148 000	176 000	184 000	212 000	293 000	–	367 000
27	3	459	152 000	184 000	193 000	230 000	239 000	275 000	381 000	–	477 000
30	3,5	561	185 000	224 000	236 000	280 000	292 000	337 000	466 000	–	583 000
33	3,5	694	229 000	278 000	292 000	347 000	361 000	416 000	576 000	–	722 000
36	4	817	270 000	327 000	343 000	408 000	425 000	490 000	678 000	–	850 000
39	4	976	322 000	390 000	410 000	488 000	508 000	586 000	810 000	–	1 020 000

Figure 49: Minimum breaking force [N] for metric coarse screw threads

This value shows the maximum amount of tensile stress that bolt can withstand before if breaks. Another table (Figure 50) shows that the nominal tensile strength of bolts is 32.9kN.

Nominell gäng-diameter mm	Delning mm	Nominell spännings-area mm^2	Sträckgräns R_{eL} N/mm² 180	240	320	300	400	480	640	$R_{p0.2}$ N/mm² 900
			Hållfasthetsklass 3.6	4.6	4.8	5.6	5.8	6.8	8.8	10.9
3	0,5	5,03	0,905	1,21	1,61	1,51	2,01	2,41	3,22	4,53
3,5	0,6	6,78	1,22	1,63	2,17	2,03	2,71	3,25	4,34	6,10
4	0,7	8,78	1,58	2,11	2,81	2,63	3,51	4,21	5,62	7,90
5	0,8	14,2	2,56	3,41	4,54	4,26	5,68	6,82	9,09	12,8
6	1	20,1	3,62	4,82	6,43	6,03	8,04	9,65	12,9	18,1
7	1	28,9	5,20	6,94	9,25	8,67	11,8	13,9	18,5	26,0
8	1,25	36,6	6,59	8,78	11,7	11,0	14,6	17,6	23,4	32,9
10	1,5	58	10,4	13,9	18,6	17,4	23,2	27,8	37,1	52,2
12	1,75	84,3	15,2	20,2	27,0	25,3	33,7	40,5	54,0	75,9
14	2	115	20,7	27,6	36,8	34,5	46,0	55,2	73,6	104
16	2	157	28,3	37,7	50,2	47,1	62,8	75,4	100	141
18	2,5	192	34,6	46,1	61,4	57,6	76,8	92,2	123	173
20	2,5	245	44,1	58,8	78,4	73,5	98,0	118	157	220
22	2,5	303	54,5	72,7	97,0	90,9	121	145	194	273
24	3	353	63,5	84,7	113	106	141	169	226	318
27	3	459	82,6	110	147	138	184	220	294	413
30	3,5	561	101	135	180	168	224	269	359	505
33	3,5	694	125	167	222	208	278	333	444	625
36	4	817	147	196	261	245	327	392	523	735
39	4	976	176	234	312	293	390	468	625	878

Figure 50: Nominal tensile strength [kN] for metric coarse screw threads

Tensile strength represents the highest point on the stress-strain curve. This is the point where a material goes from elastic to plastic deformation. Experiment should not be performed under conditions when this value is exceeded. Finally, the last table (Figure 51) shows that maximum tightening torque for those bolts is 33Nm. If this value of the torque is exceeded when tightening the bolt, then the threads of the bolt will be damaged.

Gänga M	d mm	P mm	A_s mm²	$(d + P) \cdot A_s$ mm³	Hållfasthetsklass 4.6	5.8	8.8	10.9
1,6	1,6	0,35	1,27	2,476	0,065	0,10	0,17	0,24
1,8	1,8	0,35	1,70	3,655	0,096	0,16	0,25	0,36
2	2	0,4	2,07	4,968	0,13	0,22	0,35	0,49
2,2	2,2	0,45	2,48	6,572	0,17	0,29	0,46	0,64
2,5	2,5	0,45	3,39	10,00	0,26	0,44	0,70	0,98
3	3	0,5	5,03	17,60	0,46	0,77	1,2	1,7
3,5	3,5	0,6	6,78	27,80	0,73	1,2	1,9	2,7
4	4	0,7	8,78	41,27	1,1	1,8	2,9	4,0
4,5	4,5	0,75	11,3	59,32	1,6	2,6	4,1	5,8
5	5	0,8	14,2	82,36	2,2	3,6	5,7	8,1
6	6	1	20,1	140,7	3,7	6,1	9,8	14
8	8	1,25	36,6	338,5	8,9	15	24	33

Figure 51: Tightening torque [Nm] for the bolts having the metric coarse screw threads

Purchased bolts arrived with a threaded part 30mm long. That threaded part has been extended to 50mm using. Threading process is similar to the one described for inside the holes. Difference is that this time the bolt is being threaded on the outside. For that purpose, a threading M8 x 1.25 die has been used with the handle. Threading was done by hand and prior to that threaded surface was treated with cutting oil to create smooth and nice threads.

Compression bars for the vice were manufactured in the same way as the lower bars for the base. Two segments of 160mm length were sawed off from 80x25mm solid steel bar. Those work pieces will be fabricated further to be turned into compression bars of the vice. Then all the faces of each bar have been faced in a such way that both bars ended up having identical dimensions. Facing process was performed on the conventional milling machine Luna STF-5000V (Figure 29) using 75mm facing bit at 400RPM.

Then two holes were drilled in each compression bar using Ibarmia AX – 35 pillar bore (Figure 40). Holes were centered on the largest surface of bars and spaced 100mm between each other. One bar had two holes drilled with 10mm HSS drilling bit. The second bar had both holes drilled with 6.8mm HSS drilling bit and threaded with M8 x 1.25 taper taps. Details on drilling and facing procedures have been thoroughly described earlier in the report and are not repeated.

As a final step, both compression bars have been polished in the same manner as parts for modular molding construction described before. Visual representation and dimensions of the final products are given on the following figures. Figure 52 is showing the compression bar with threaded holes and figure 53 is showing a bar with holes that are not threaded. Dimensions are represented in millimeters.

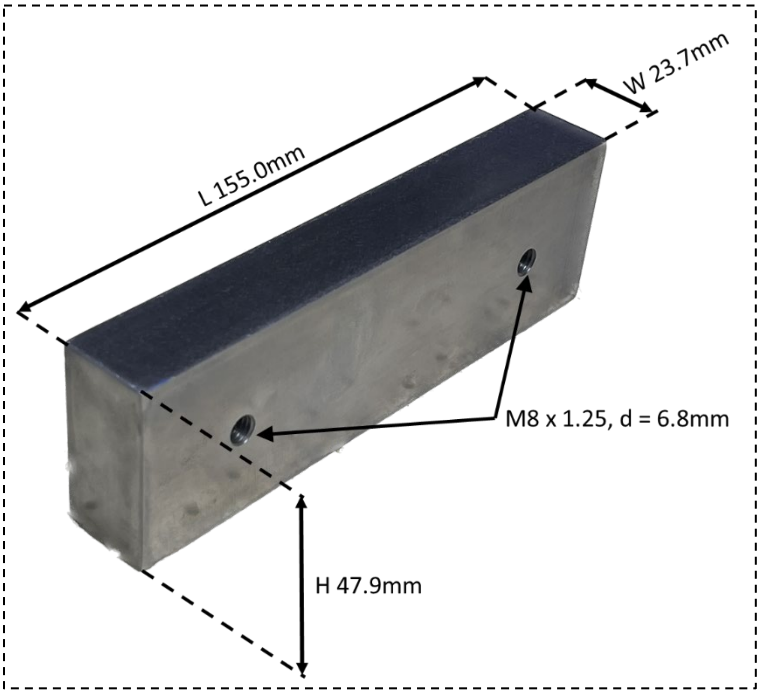


Figure 52: Dimensions of compression bar with threaded holes

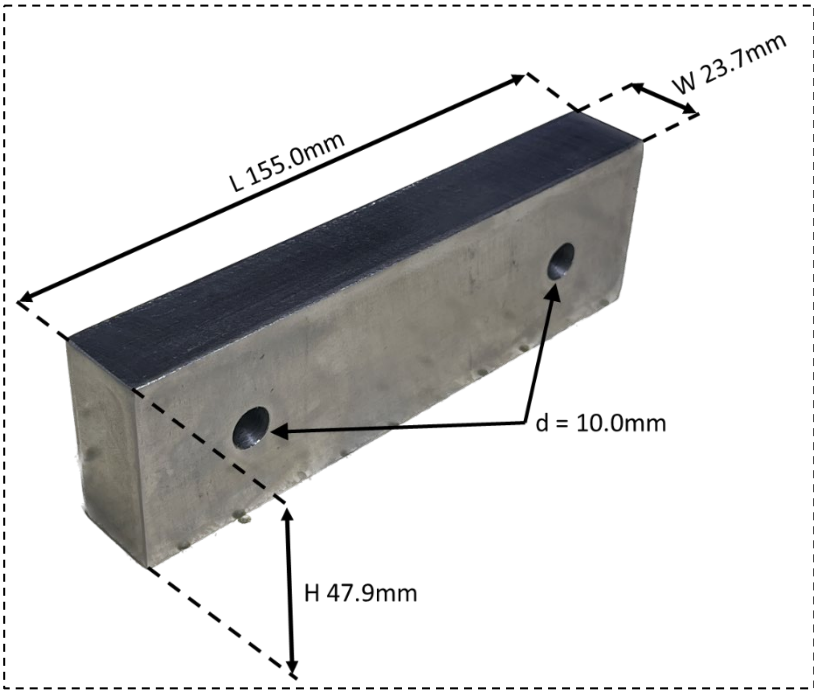


Figure 53: Dimensions of compression bar with holes that are not threaded

At this point, the fabrication of all the components for the vice is complete. The next step will be assembling them all together including pressure load cells that are going over each bolt. This further procedure is described in section 3.1.4 of this research.

2.3 Electrical wiring for compression washer load cells

This section describes electrical wiring for the compression washer load cells used to acquire the data for the compression load during the rectangular pushout experiments. Main elements the electrical setup include:

- Compression washer load cells Sensy model 5182-B, two pieces
- Measuring amplifiers Clip model AE301, two pieces
- Multimeters Fluke morel 179, two pieces
- Switching power supply unit Mean Well model SP-320-24

Additional materials include:

- Electrical cable 1.5mm2, various colors
- PG7 Cable Glands
- 2-DIN rail mount 223mm long
- Banana plug type multimeter test leads
- Heat shrinkable tubes
- Plastic cable hiding box with lidL400 x W150 x H130
- Insulated female round connectors
- Polypropylene flex hose for protecting electric cables

Compression washer load cells are specially designed for force measurement on bolts. Two load cells model 5182-B (Figure 54) have been ordered from Sensy with a maximum load capacity of 30kN and

Figure 54: Compression washer load cells in their original package

hole diameter of 8.1mm for measuring force on M8 bolts. First cell with serial number 2220687000 will be further referred to as load cell 1. The second cell with serial number 2220687001 will be further referred to as load cell 2. Cells arrived with two stainless steel washers included in the package for each cell. Figure 55 shows schematic of compression load cell taken from producers' website. Figure 56 shows the load cells mounted on the bolts. Red marker was used to mark load cell 1 to make it easier to distinguish between two of them. Included in the package was also a control certificate from producer which ensures that both cells have passed the quality control test. This certificate can be reviewer in the appendix

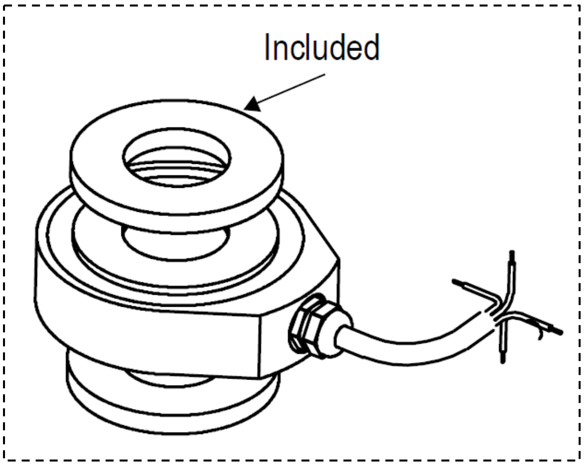


Figure 55: Technical drawing of compression washer load cell Sensy model 5182-B

Figure 56: Load cell attached on the bolts including washers

Measuring amplifier Clip model AE301 (Figure 57) have been used to deliver power to the load cell and process the signal incoming back from cell. Maximum power output this amplifier can deliver is

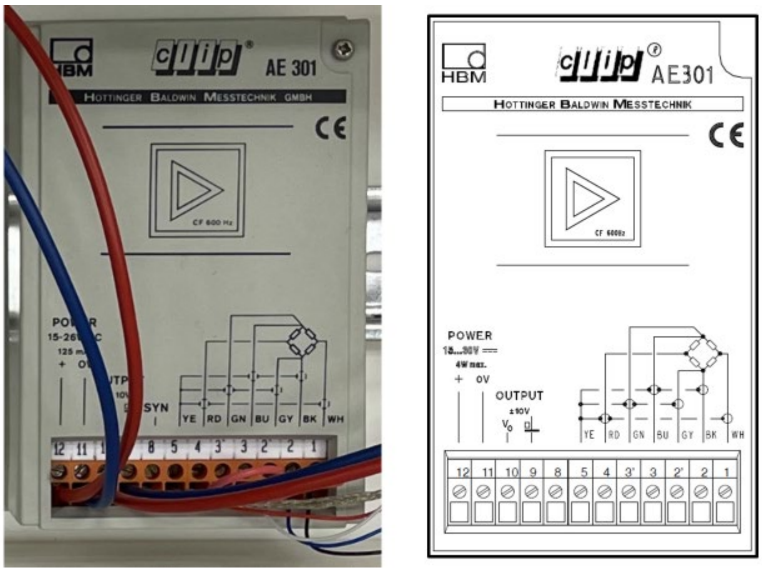


Figure 57: Measuring amplifier Clip model AE301 picture (left) and (technical drawing)

4W. Table on the figure 58, taken from the operation manual of measuring amplifier, describes the functions for the terminals on the amplifier. Amplifier has been connected using a 4-wire circuit therefore terminals 2 and 2’ and 3 and 3’ have been bridged with short jumper wires.

Type	AE101, AE301, AE501	
Terminal	**Function**	**Color (HBM - cable)**
1	Measuring signal	WH (white)
2	Bridge excitation voltage	BK (black)
2'	Sensor line	GY (grey)
3	Bridge excitation voltage	BU (blue)
3'	Sensor line	GN (green)
4	Measuring signal	RD (red)
5	Screen/Ground	YE (yellow)
8	Synchronization (not with AE101)	
9	Operating-voltage zero*)	
10	Output voltage	
11	Supply voltage zero*)	
12	Supply voltage	

Figure 58: Measuring amplifier connection

Fluke 179 multimeter (figure 59) is connected to terminals 9 and 10 of the measuring amplifier and set to measure DC voltage. Measured voltage is then displayed on the screen of multimeter. Output signal from cell is voltage between 0-10V.

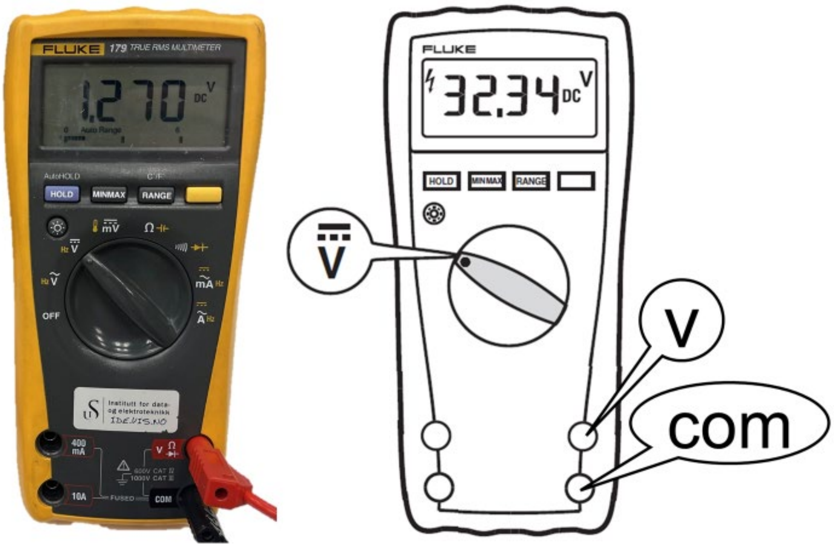


Figure 59: Fluke 179 multimeter picture (left) and (technical drawing)

The final piece of the whole puzzle is switching power supply unit from Mean Well model SP-320-24. It has 240V 5A AC input and delivers 24V 13A DC output. Maximum power output is 312W.

Due to the high cost of load cells and long delivery dates, electrical engineer was consulted before process of wiring the electrical setup for the pressure load cells can begin. It was made sure that all the wires are going to correct terminals to avoid the damage of the equipment. Figure 63 is showing a schematic over the whole electrical setup. Everything starts with the power supply unit that is connected to 240V AC mains of electric power supply in the building. This power unit delivers 24V DC to both measuring amplifiers through positive and negative output terminals as shown on figure 61. Each measuring amplifier has a multimeter connected to it through terminals 9 and 10 on amplifier that are going to COM and V terminals on the multimeter respectively. Each

Figure 60: Switching power supply Mean Well model SP-320-24

compression washer load cell is connected to its amplifier through terminals 1-5 on the amplifier as shown on the figure 63.

At this point description of the wiring diagram for compression washer load cells was given. All electric components have been organized in a clean and user-friendly way as shown on the figure 61 below.

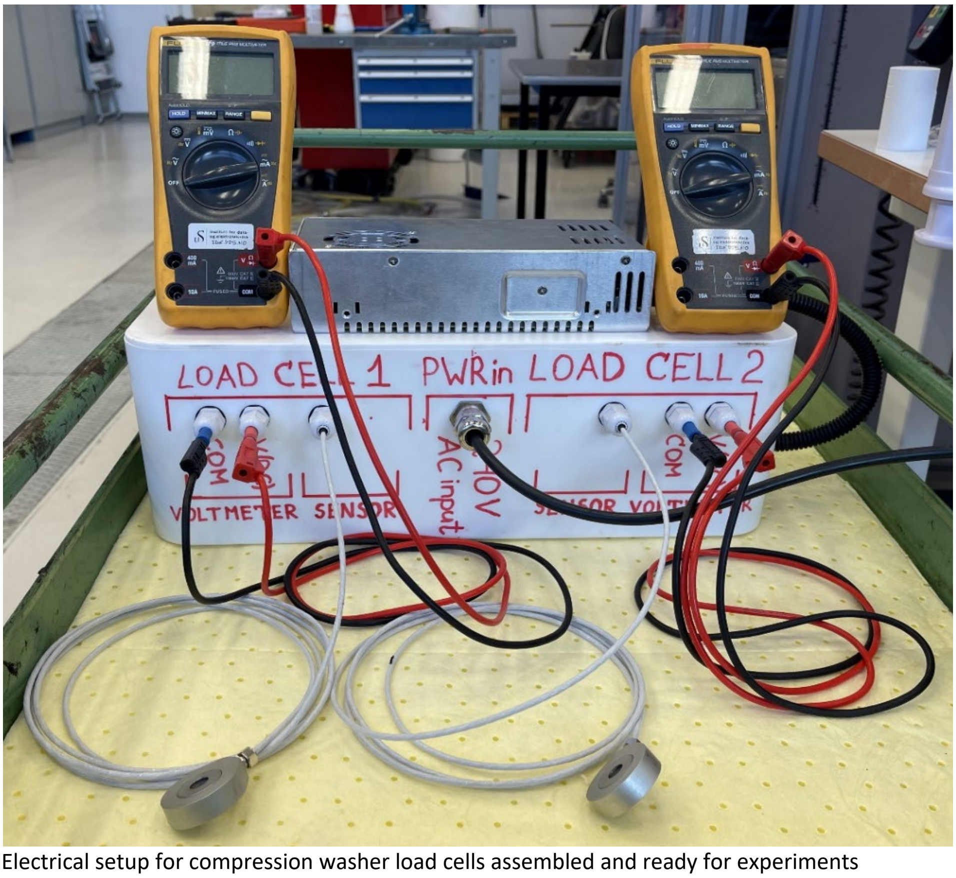


Figure 61: Electrical setup for compression washer load cells assembled and ready for experiments

Assembly of electrical setup was started with plastic box for hiding cables. Seven holes were drilled in the box where PG7 cable glands were then mounted. 2-DIN 223mm long rail mount was secured at the bottom of the box using small bolts and nuts. Measuring amplifiers were then mounted to the rail at the bottom of the box.

Power supply unit was too large to be mounted inside the box, so it was attached to the outer side of the lid that came with the box. Power cable with electrical outlet plug was run with a free end through the gland in the middle and then attached to G (Ground), N (Neutral), L (Live) AC input terminals on the power unit.

Cables from sensors were run through PG7 glands and connected to their respective measuring amplifiers through terminals 1-5 as shown on the figure 63. Insulation on wires were stripped about 1cm and twisted by hand before inserted into terminals and secured using screwdriver and securing bolts. Terminals 2 and 2’ and 3 and 3’ on the amplifiers have been bridged with short jumper wires.

Short wires were attached to terminals 9 and 10 on the amplifier. Insulated female round connectors were attached to the free ends of those wires and then secured in remaining cable glands. Banana plug type multimeter test leads can be inserted or removed into those connectors to connect or disconnect multimeters to measuring amplifiers. Wires going through the terminal 9 and 10 can be connected or disconnected to COM and V terminals of multimeter.

Another set of wires was used to connect amplifiers to the power unit. Terminals 11 and 12 on the amplifiers were connected to -V (negative) and +V (positive) output terminals of the power supply unit. Wires connecting amplifiers with power supply unit along with the power cable were collected inside black polypropylene flex hose. Finally red permanent marker was used to mark connections on the outside of the box to give the whole setup cleaner and more organized look. Figure 62 shows detailed view of electrical setup with the lid of the box removed and multimeters disconnected.

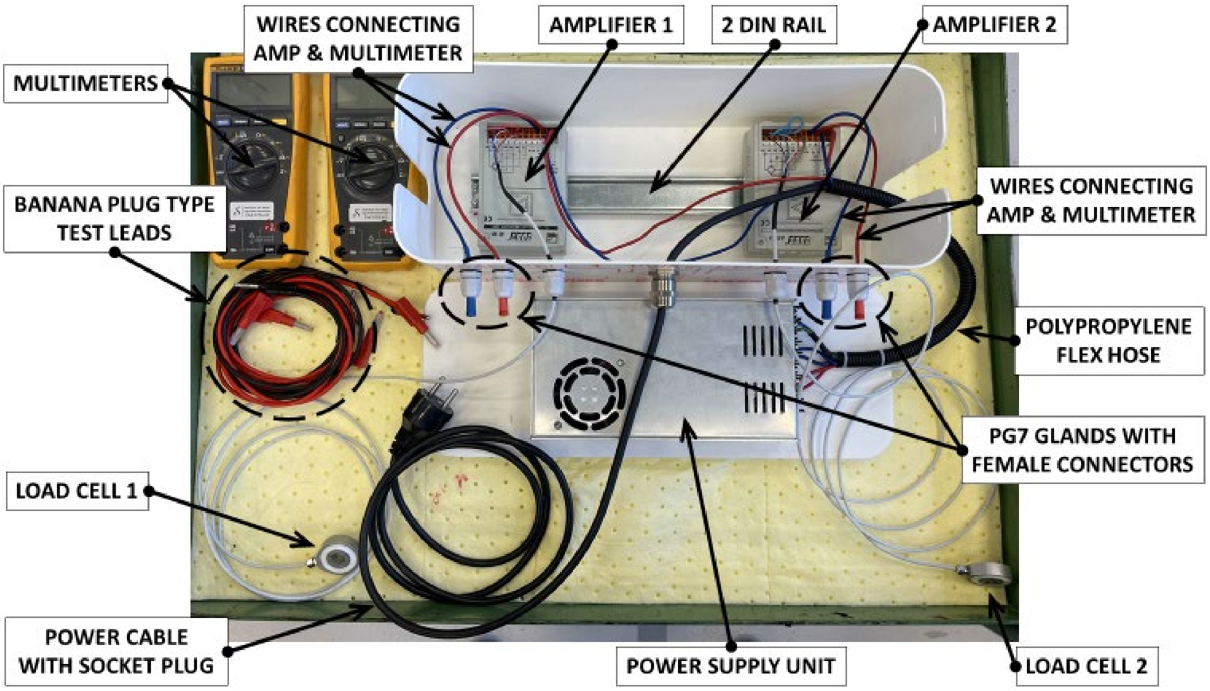


Figure 62: Electrical setup for compression washer load cells, detailed view

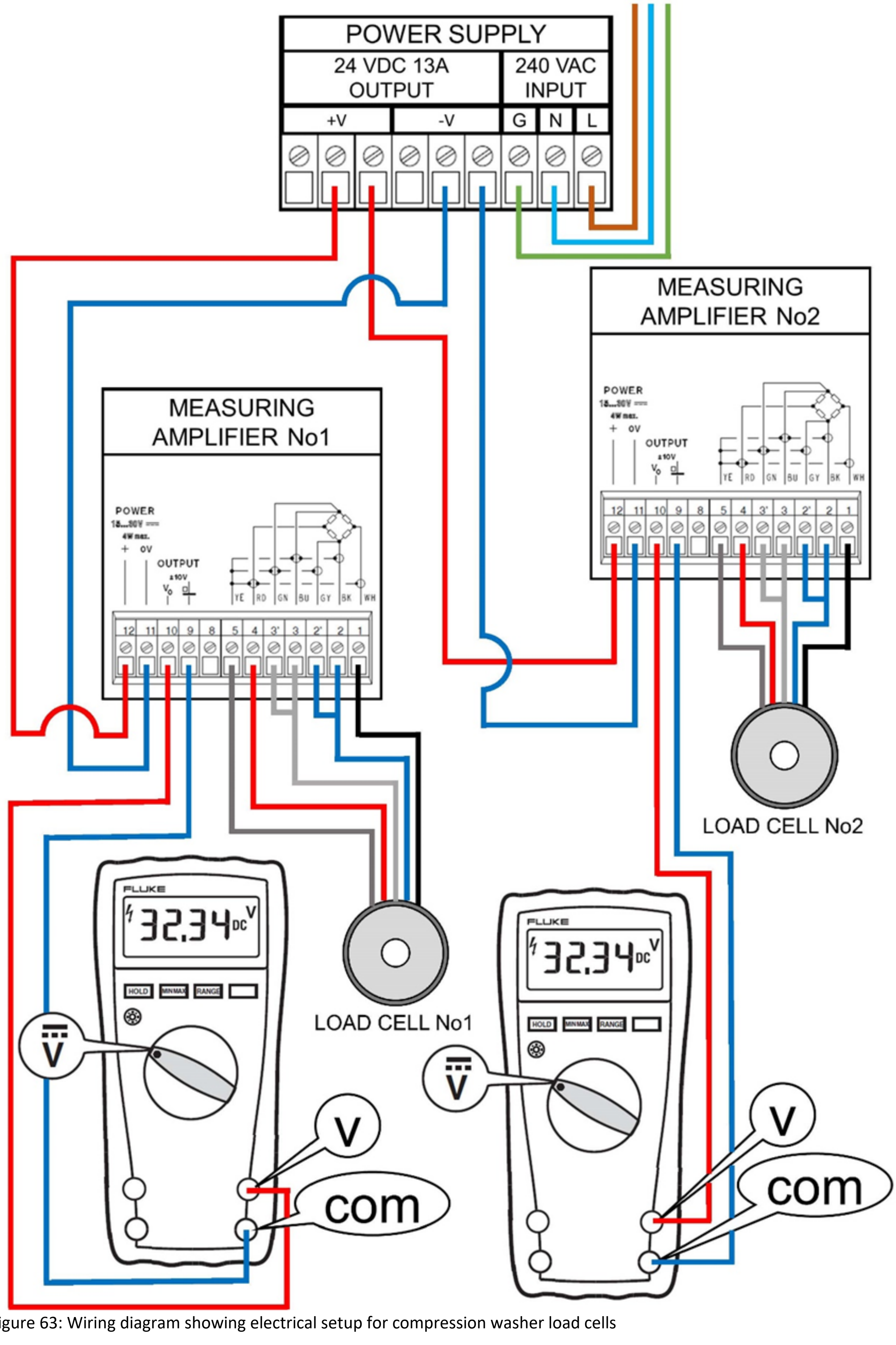


Figure 63: Wiring diagram showing electrical setup for compression washer load cells

2.4 Construction for conventional friction experiment

Figure 64 shows detailed overview of construction for conventional friction experiment and its main components. It basically consists of two plates. Base plate located at the bottom serves as a

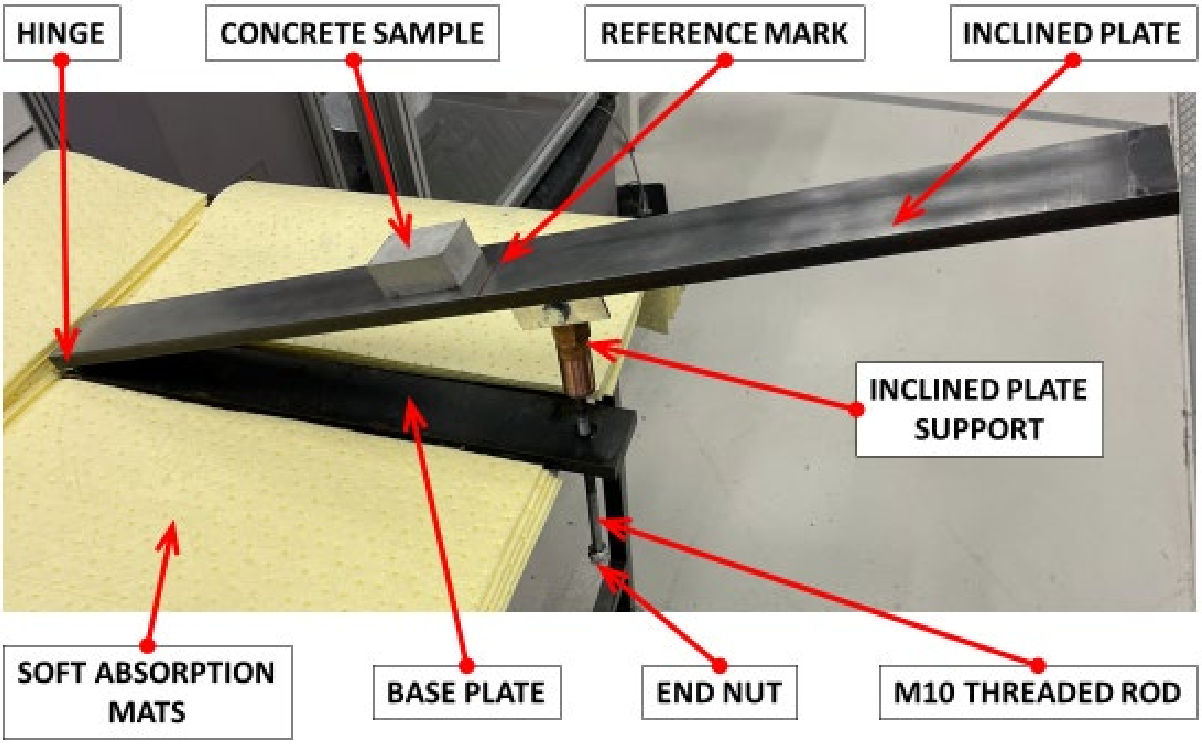


Figure 64: Construction for conventional friction experiment, detailed sketch

fundament for the whole construction. It is connected to the inclined plate using the hinge so that the angle between two plates can be adjusted. Both base plate and inclined plate have been cut from the same fabrication rod as the sliding plate in modular molding construction. It was done using horizontal metal cutting band saw have been used. Base plate was cut 53cm long and inclined plate was cut 90cm long. Afterwards the upper surface of inclined plate has been sanded down using surface grinding machine Bernardo BSG 2040PLC that has rotating grinding stone (Figure 65).

Figure 65: Surface grinding machine Bernardo BSG 2040PLC

Adjustment of the angle between both plates is done by rotating threaded rod that goes through a threaded hole at the corner of the base plate, on the opposite side of the hinge. Threaded rod goes inside mechanism of inclined plate support (Figure 66). Inclined plate is resting on that mechanism

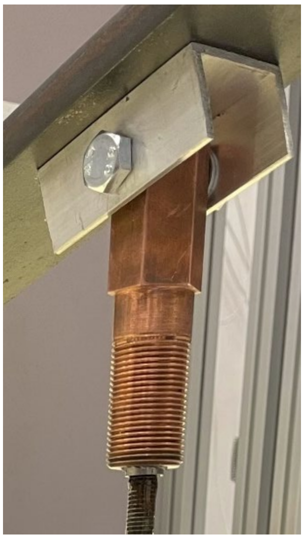


Figure 66: Inclined plate support mechanism

under its own weight. Inclined plate support mechanism consists of two elements that are connected using M10 bolt forming a flexible joint between them. Lower element has an opening at the bottom where the threaded rod is spinning freely inside. Upper element is a simple piece of U-profile aluminum bar. Upper element is not fastened to the inclined plane by any means. Inclined plane is resting on the top of it just under its own weight. As the angle is changed between base and incline plate, surface of U-profile bar and inclined plane are sliding against each other, and the angle of U-profile bar is also changing. At the bottom end of threaded rod are two M10 17mm nuts

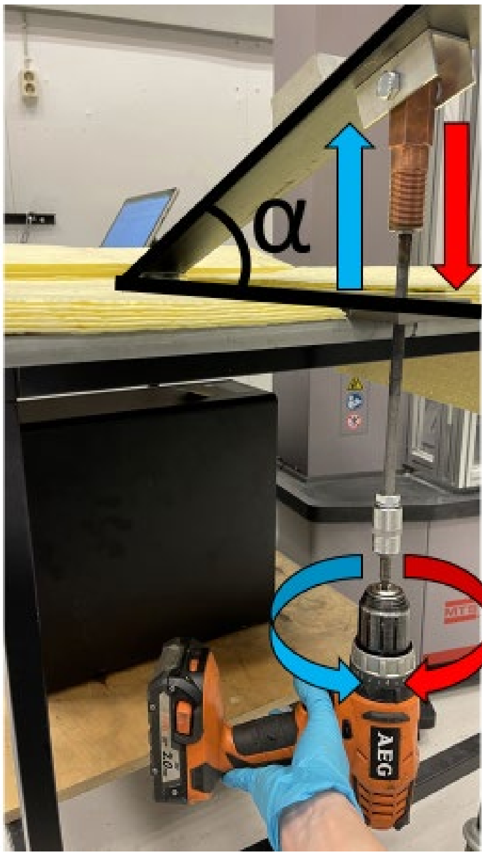


Figure 67: Adjustment of angle ‘α’ between plates using power screwdriver

tightened against each other. Power screwdriver with attached 17mm socket is used to spin the threaded rod (Figure 67). As the power screwdriver goes in the clockwise direction; the inclined plane is being lifted from one side and thus angle ‘α’ between both plates increases. To lower inclined plate and decrease the angle ‘α’ between both plates, power screwdriver is set to rotate in anti-clockwise direction.

3. Description of experimental procedure and equipment

Three types of experiments have been conducted as the part of this scientific research:

- Pushout tests on the rectangular assembly with sliding plate compressed in between the blocks of concrete sample
- Conventional friction tests on an inclined plane
- Pushout tests on the radial assembly

In this section, description of experimental procedure and equipment will be provided for all three experiments in the same order as they been listed.

3.1 Experimental procedure and equipment for pushout tests on the rectangular assembly

This experiment has been started with pre-experimental procedures and preparations including:

- Calibration of compression washer load cells
- Roughness measurement of sliding plate
- Concrete sample production for pushout tests on rectangular assembly

3.1.1 Calibration of compression washer load cells

After the electrical wiring setup (Section 2.3) for compression washer load cells was complete, cells must be calibrated. As the load is applied to a cell, a multimeter is showing a DC voltage that corresponds to that load. As the applied load is changed, the voltage changes. There is a certain relationship between the load applied on the cell and the voltage displayed on the voltmeter. This relationship needs to be found to interpret voltage readings into the load applied on the cell during the pushout tests. This was done by applying certain fixed loads to a load cell and then registering the corresponding voltage readings it produces. For this purpose, Universal testing machine Zwick/Roell ProLine Z050 was used together with Xforce K load cells from the same producer (Figure 68). This machine has been calibrated the same month before the calibration procedure of the load cells described in this section.

First, electrical setup for load cells was prepared. It was connected to 240V AC electricity mains in the lab. Then both multimeters were connected using banana plug type multimeter test leads that are going from COM and V terminals of the voltmeter into the corresponding marked female rod connectors outside the electric box (Figure 69). Then multimeter is set to measure DC voltage. Load cell is then placed on the testing stand inside the cabinet of universal testing machine. Then the gate of the cabinet is closed and software interface for testing machine was opened on the computer. A pattern for compressive tests has been chosen. Parameters have been chosen in a such way that machine executes compression load on the cell in a stepwise manner. Preset loads of 0.5; 1.0; 1.5; 2.0; 2.5 and 3.0 kN were chosen. Once machine is set to run, it starts by applying the smallest load of 0.5kN and holds this load for 15 seconds. Then it moves on to the next load which is 1.0kN and holds it for 15 seconds again. This procedure is repeated until it reaches the load of 3.0kN and holds it for the last 15 seconds. Then the test is over and piston of the press returns to its initial condition. During the 15 seconds that machine is holding the load, the voltage reading on the multimeter sets

Figure 68: Universal testing machine Zwick/Roell ProLine Z050 with Xforce K load cells

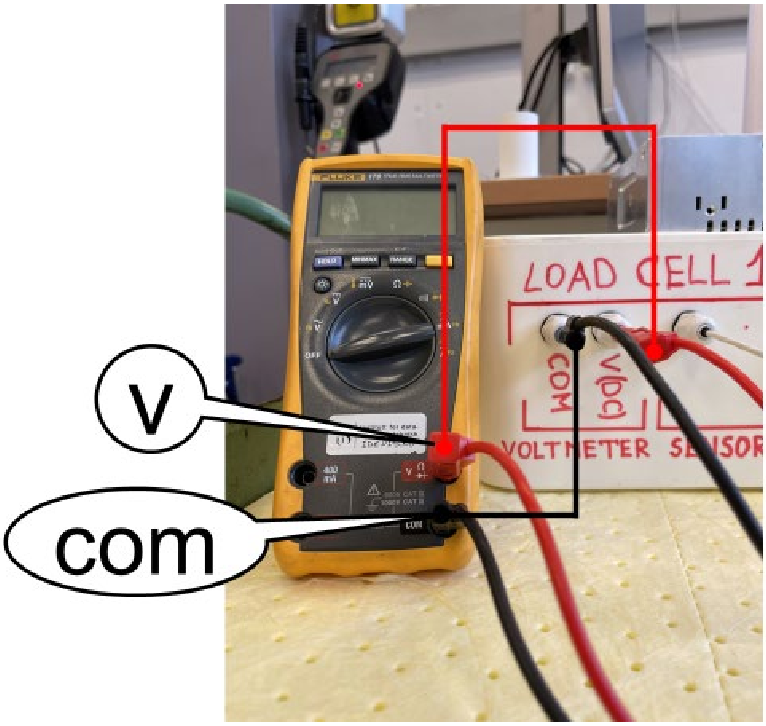


Figure 69: Connecting multimeter to measuring amplifier

down and is recorded before machine jumps to the next load. The initial voltage of cell when there was no load applied to it was also recorded. This procedure was repeated five times for each of two cells. Gathered data of compression load vs voltage measured was collected in the data tables 2 and 3 that are presented in the section 4.1. Gathered data was later plotted and relation between compression load and voltage evaluated. Then the voltage measurements logged during pushout tests on the rectangular assembly can be converted into the load measurements in [kN].

3.1.2 Roughness measurement of sliding plate

Sliding plate is a part of modular construction for cement moulding. It is also later used in the pushout tests on the rectangular assembly where sliding plate compressed in between the blocks of concrete sample is being pushed down on MTS machine. Roughness of the surface of sliding plate was measured once before it was started to be used in experimental work. Measurements are taken using ISR-C300 INSIZE Roughness Tester (Figure 70). Device consists of probe connected to main unit with the wire.

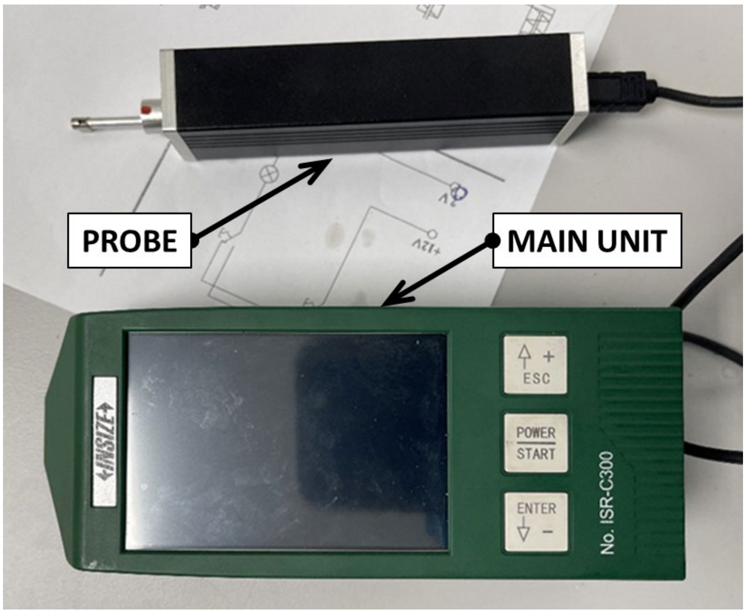


Figure 70: ISR-C300 INSIZE Roughness Tester with separable probe and main unit

Before roughness measurements can be taken, surfaces of sliding plate were prepared as shown on the figure 71. Newly fabricated sliding plate had it’s both largest surfaces polished with medium grid

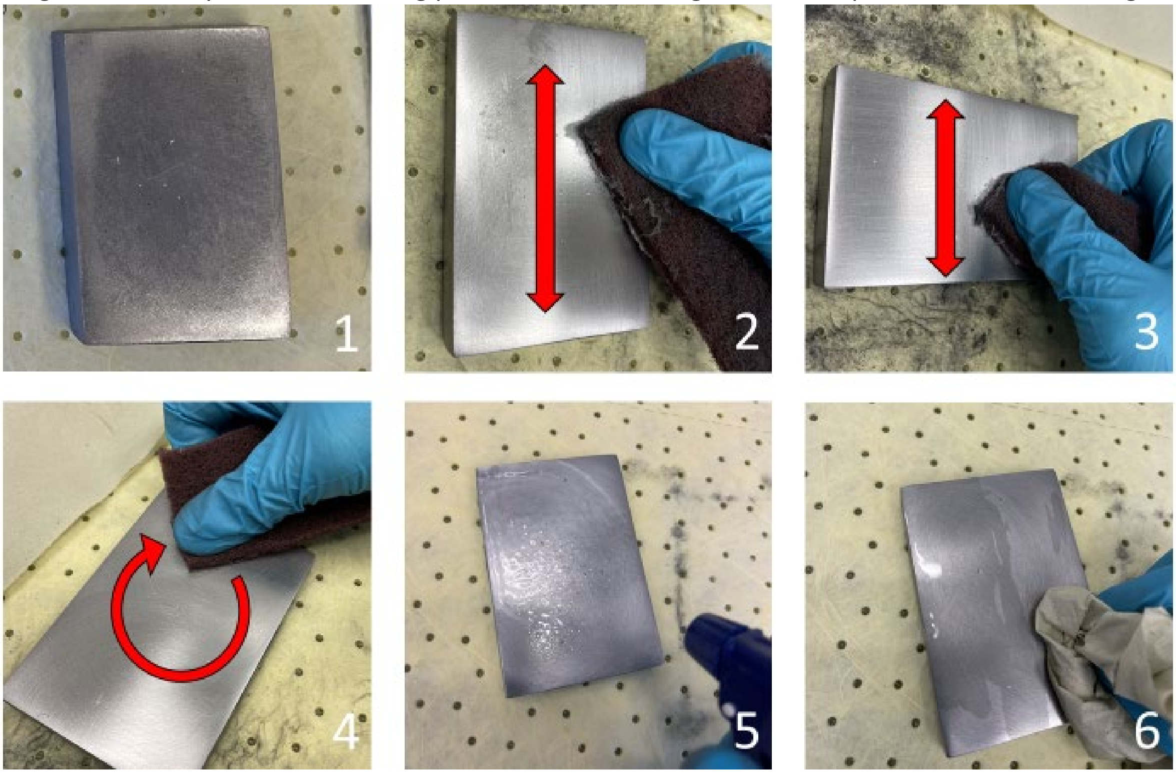


Figure 71: Treating surfaces of sliding plate with medium abrasive sheet, stepwise instructions

abrasive sheet (steps 2 – 4 on figure 71). First surface was polished in lengthwise direction (step 2), then thwartwise (step 3) and finally in circular motion (step 4). Red arrows on the figure 71 are showing the direction of movement of abrasive sheet. After polishing process, sliding plate has been treated with 85% ethanol solution and wiped dry with paper towels (steps 5 – 6).

Roughness measurements are taken at the tip of the probe. Then result is displayed on the main unit and noted down. Roughness tester displays two values Ra and Rz as it measures roughness in two directions: parallel to the probe (Ra) and perpendicular to the probe (Rz) respectively. For this experimental setup the value Ra is the roughness measured parallel to the longest side of the sliding plate. Ra is the value of interest for this investigation as the plate will be sliding along the longest side. During the test, probe was taking five measurements in a pattern (Figure 72) at both largest sides of the sliding plate: upper and lower. Results were collected in the table 6 section 4.2.

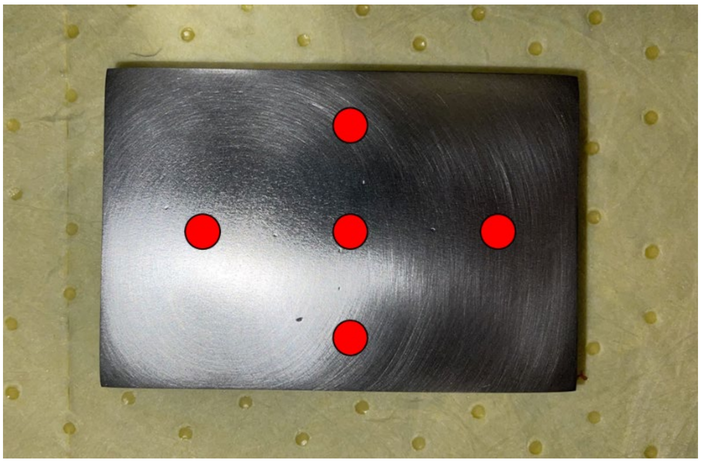


Figure 72: Pattern for taking roughness measurements on sliding plate, red dots showing locations for the probe

3.1.3 Concrete sample production for pushout tests on rectangular assembly

Production process for concrete samples later to be used for pushout tests on rectangular assembly consists of two parts: cement mixing procedure and procedure for molding concrete blocks. Both procedures must be performed one right after another. After the cement mixture has been created, it takes very little time before it begins hardening and turns into solid concrete. Both procedures are described below.

3.1.3.1 Cement mixing procedure

Dyckerhoff API class G well cement of high sulfate-resistant (HSR) grade and Waring commercial blender were used to prepare cement mixture for all experimental procedures executed as a part of this research:

- plugs used in radial pushout experiments
- rectangular molded concrete samples used both in pushout tests on rectangular assembly and conventional friction tests on an inclined plane

Cement lab at the university premises has been used for mixing cement. Proper course and training must be taken to execute procedure safely in accordance with HSE requirements.

Before carrying with procedure, the risk assessment and safety datasheet for cement used have been thoroughly studied and SJA (safe job analysis) form has been filled out. SJA form also includes risk assessment related to MTS machine used later. All those forms are attached in the appendix where they can be reviewed more closely.

Class G cement has following hazard statements:

- H318 Causes serious eye damage
- H315 Causes skin irritation
- H335 May cause respiratory irritation

Therefore, it is important to prevent cement dust of getting inside the eyes, on skin or getting inhaled into lungs. Waring blender also has sharp blades rotating at high speeds (up to 12000RPM) and must be handled with care. Proper precautionary measures must be taken when handling cement. Experimental procedure must be followed carefully as well as proper protective equipment must be used. Protective equipment used during cement mixing procedure includes fume cupboard, 3M safety goggles, latex gloves and 3M reusable half mask CE2797 with two 3M particulate filters 6035. Experiment procedure was carried in accordance with the lab procedures specified by the American Petroleum Institute (API) standards. After fulfilling the relevant safety and training courses and getting SJA form approved by the senior engineer at university the procedure can finally be safely carried out.

Stainless steel container with blade (Figure 73) was taken and inspected for mechanical damages by spinning blade by hand.

Then this container was about 1/3 filled with tap water and set on the Waring blender located inside the fume cupboard (Figure 74). It is very important to check that container with blades is securely attached on the blender as it has parts spinning at very high speeds. Container must rest perfectly

Figure 73: Stainless steel container with blade

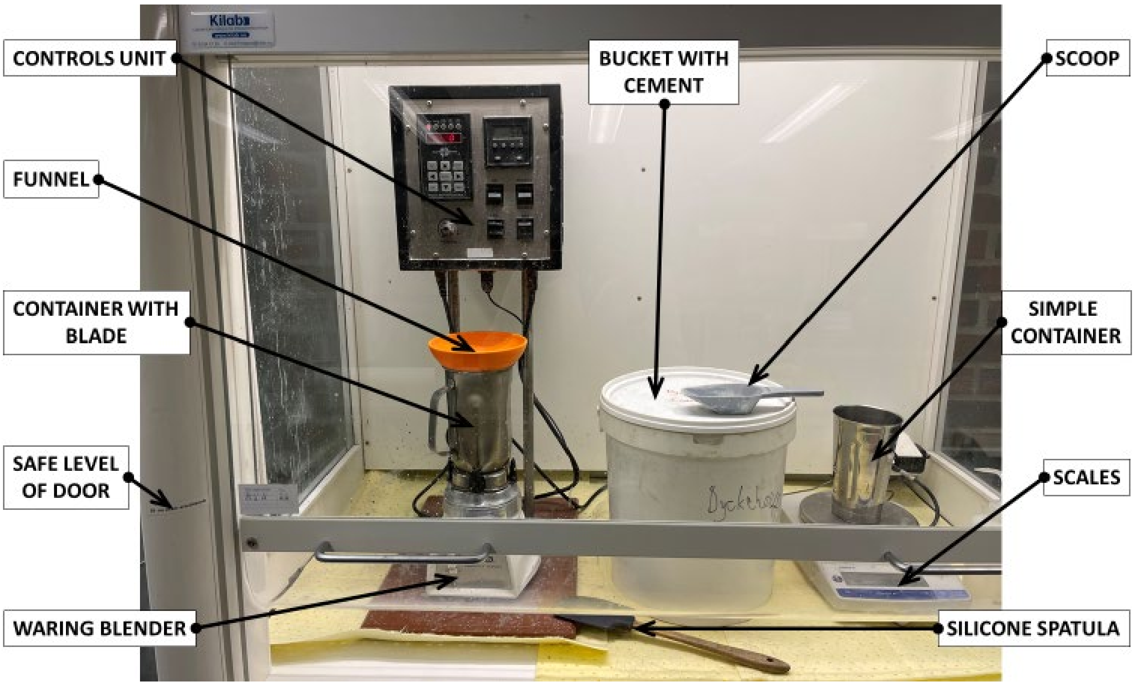


Figure 74: Setup for cement mixing procedure inside fume cupboard

vertically on the blender. By no means container should be tilted to the side. Blender includes guiding teeth that help in the secure installation of the container. Improper attachment of container to the blender may lead to serious injuries and damage of the equipment.

After the secure attachment of container, blender was set to run between 15-20s at 4000 RPM to thoroughly clean the container and then stopped. Container is then removed from the blender and dried using air gun with compressor and cleaning paper.

348.0g of distilled water was weighted into clean and dry container on the lab scales. Then this container was carefully attached on the top of the Waring blender inside the fume cupboard (Figure 74). At this point mask with particulate filter must be used to carry on with handling the cement.

A plastic bucket with the lid containing API class G cement was placed inside the fume cupboard.

Another simple stainless-steel container without blade (Figure 74) was set on the scales inside the fume cupboard. Then the scale had been tared to zero out the weight of the empty container.

Glass door of the fume cupboard was then lowered below 28cm mark to the safe operational position (Figure 74) before the lid of the bucket was opened.

Then a scoop was used to weight 792g of cement from the bucket into the empty container. After that the lid was closed and the bucked removed out of the fume cupboard back to its storage place.

At this point actual cement mixing process can begin. Blender is programmed in a such way that it starts rotating at 4000RPM during 15s and then it goes up to 12000RPM for 35s.

Before the blender is started the funnel (Figure 74) is put at the top of the container filled with water. Then the blender is started and during the first 15 seconds at lower 4000RPM, all the contents of container with cement must be emptied into the container on blender. Silicone spatula is used to help putting cement into the container. Then the blender rotates at 12000RPM for 60s and automatically stops.

Then the funnel was removed, and the container can be taken out from the blender. It is important to keep stirring the cement mixture with silicone spatula until it is poured into the molding shape because it is hardening quickly.

3.1.3.2 Procedure for molding concrete blocks

Modular molding construction has been manufactured for molding rectangular cement blocks used in rectangular pushout experiments and conventional friction experiment. Molding construction consists of seven main elements: four side walls, top and bottom plates and sliding steel plate (Figure 75) that are held together using four threaded rods and nuts. Technical specifications such as dimensions and manufacturing process of this construction are described in section 2.1.

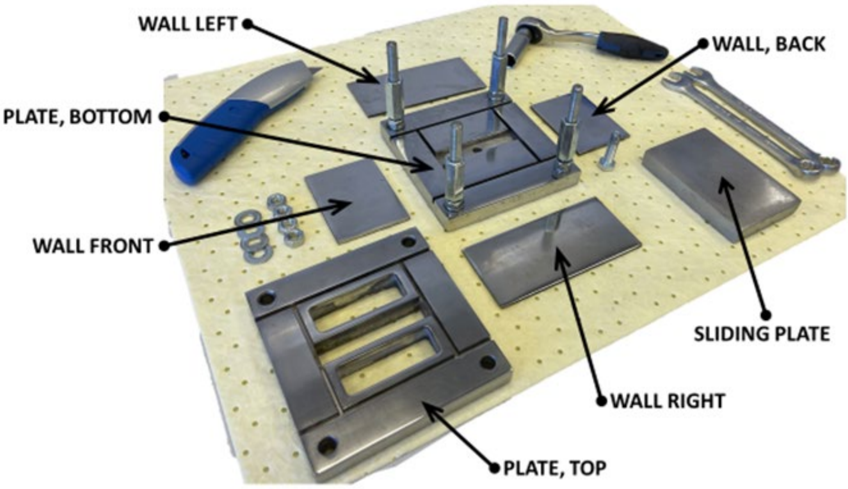


Figure 75: Modular molding construction disassembled

In the beginning the construction was completely disassembled (Figure 75). But before the first assembly process, all inner surfaces that will be in contact with the cement have to be covered with transparent tape as well as the hole in the middle of the bottom plate. Exception is the sliding plate that will be in contact with the cement during the curing process and thus it is left uncovered with the tape. The excess of the tape has been cut around edges using the sharp blade of utility knife

(Figure 76) so that it does not get jammed in the connections. Transparent tape is applied to preserve the metal parts of the construction as well as to make later disassembly process easier. Cement is sticking much less to the tape than uncovered metal surfaces that it makes stronger adhesion with.

Figure 76: Cutting the excess from the tape applied to surfaces of the bottom plate contacting cement

The bottom plate is used as the base for the whole construction. The side with the grooves on the bottom plate must be pointing upwards.

Then the walls can be fitted inside the grooves on the bottom plate like blocks of LEGO. Front and back walls are shorter and are fitted in the shorter grooves. Right and left walls are longer and are fitted in the long grooves respectively. The result should look like on the figure 77.

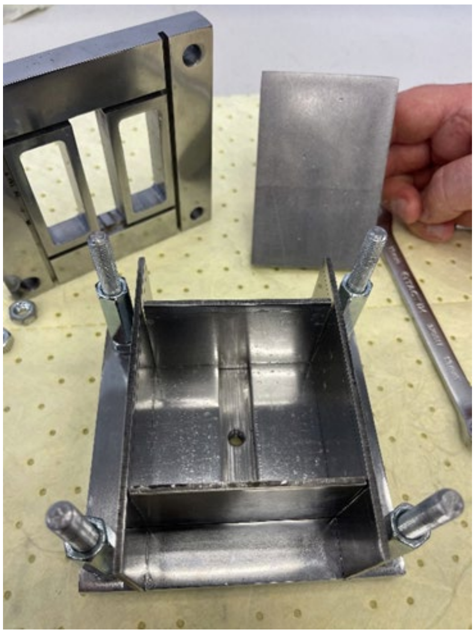


Figure 77: Walls are fitted into the grooves of the bottom plate

At this point the top plate can be fitted at the top with the grooves aligned with the walls. Threaded rods should fit through the holes made in the corners of top plate. Then the plate is secured with four nuts and washers that are screwed on the rods. Each of the nut is tightened with ¼ inch socket wrench with 13mm Hex socket. Last piece in the 'puzzle' is a sliding plate that is inserted into the middle hole of the top plate until it goes into the groove in the middle of the bottom plate. When the molding construction is assembled it should look like on the figure 78.

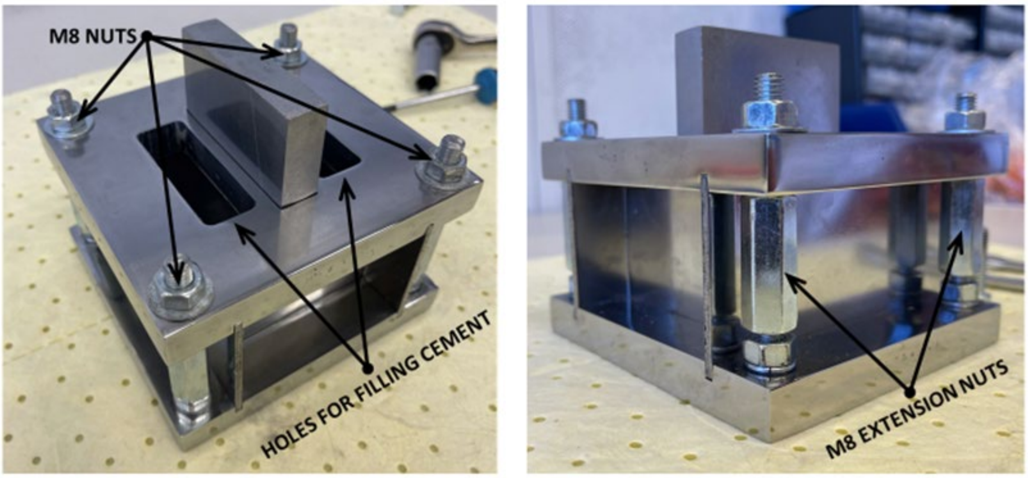


Figure 78: Assembled modular cement molding construction

The next step after modular molding construction assembly is the preparation of cement mixture described in section 3.1.3.2. The construction was assembled first to minimize the time cement mixture is staying in the blender container. If cement gets hardened in the container it will be impossible to use it for filling up the molding construction.

Modular construction is then filled up with the freshly prepared cement mixture though both holes at the top. Tiny funnel was used to prevent cement spilling from container and all over the construction and table. Holes for filling the cement are 15mm thick and each of them are filled until there is approx. 10mm left. Construction is not filled until the cement mixture is spilling above the top. The 10mm space was left to be filled up with water. API class G well cement needs to stay wet during the curing process. If cement is drying out, then it will be losing its strength. Therefore, it is important to always have some free water over the top of the cement during curing process. Water is being added very carefully with the help of pipette not to disturb the cement mixture at the bottom. As the water level reaches the top of the plate, holes are covered over the top with transparent tape (Figure 79).

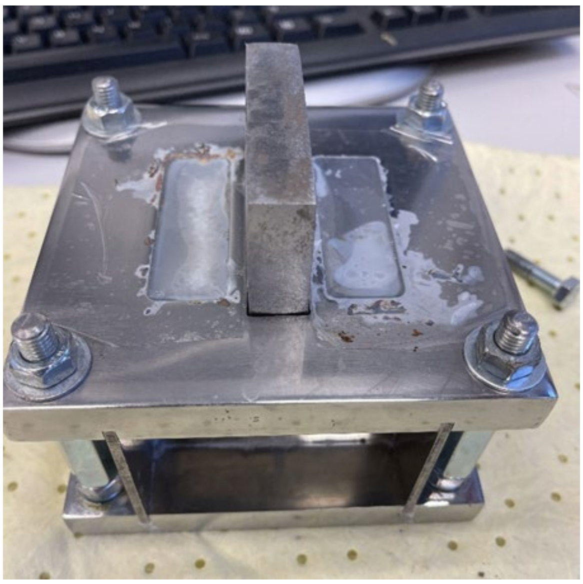


Figure 79: Filling holes at the top plate covered with transparent tape

The curing time for cement was set to one week. During this time the water at the top would all evaporate into the atmosphere if holes are left open to surroundings.

After one week elapsed, the sample is ready to be extracted from the molding construction. The disassembly process of construction begins by unscrewing and removing nuts and washers that secure all pieces of construction together. But still all the parts are strongly held together by the force of adhesion between cement and steel.

First, top and bottom plates are separated from each other. This is done by turning the M8 extension nuts (Figure 78) with 13 mm wrench. Each extension nut is turned counterclockwise half-turn one after another until the bottom and top plates slowly separate one from another. Nuts must be turned in a such way that plates are being separated equally at all corners. If the plates are wrenched out too much on one side, there is a risk of damaging the concrete sample.

Bottom plate is going off easier than the top plate as filling holes provide more adhesion between cement and top plate (Figure 80). After removal of the bottom plate, the walls can be removed just

Figure 80: Bottom plate removed from the molding construction and cement sample got exposed

by wiggling them a little bit with a hand. Now there are left only two cement blocks with the sliding plate in between attached to the top plate. To carefully separate them, the whole assembly was flipped upside down and mounted back over the bottom plate in a such way that threaded rods from the bottom plate were aligned with the holes in the corners of the top plate (Figure 81).

Two tiny pushout metal blocks (Figure 81) were inserted under the filling holes so that they were touching cement blocks at the top and bottom plate at the bottom. Then the top plate was let resting on those pushout blocks. Then M8 bolt was screwed through the threaded hole in the middle of the bottom plate until it got into contact with the sliding plate. Extension nuts were screwed over the free ends of the four threaded rods by hand until the resistance was felt.

At this point cement blocks are supported from below with tiny pushout blocks and sliding plate is supported with M8 bolt going through the middle of the bottom plate. This was done to prevent the movement of the sliding plate relative to concrete blocks as such a movement may alter measurements taken further during experiments. Surface of concrete blocks that was in a contact with sliding plate must remain intact before the start of friction experiments.

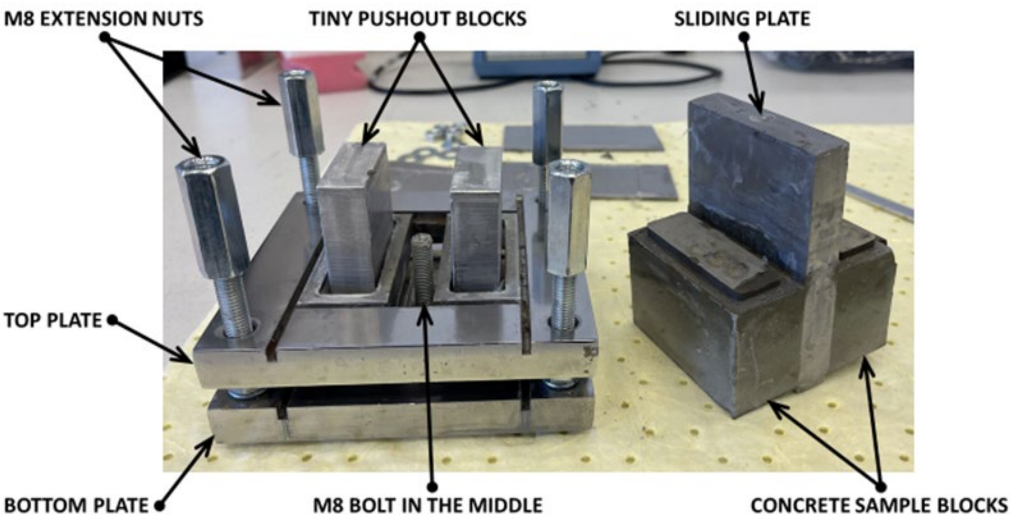


Figure 81: Concrete blocks and sliding plate as a single piece separated from the top plate

After the relative movement between cement blocks and sliding plate is prevented, the separation of cement blocks from the top plate can begin. This was done by turning extension nuts in clockwise direction with 13mm wrench. Nuts are wrenched half turn one after another in a such way that the top plate is being pushed downwards while the position of a sliding plate and cement blocks remains stationary relative to the bottom plate. Both top and bottom plates must stay as parallel to each other as possible while the top plate is being pushed closer to the bottom plate. This results in cement blocks and sliding plate being separated from the top plate (Figure 81).

For only one sample out of seven, both concrete blocks and sliding plate were still attached all together after being separated from the top plate (Figure 81). For the rest of the samples, it was observed that only one concrete block was left attached to the steel plate while the other one was free. This happens due to slight variations in level of cement filling both sides of molding construction. Any cement blocks attached to sliding plate can be easily separated using hands.

Finally, both cement blocks were extracted from the molding shape. They were then put inside the plastic container that was filled with water to completely cover both blocks. The lid of the contained was closed and sample is being stored in a such way under the room temperature and atmospheric pressure while it is not being used in experiments. Pair of molded cement blocks from the same batch are making up each sample. During the research a total of seven samples were produced. Table 1 has a list with the date of samples being produced.

Table 1: Production date of the samples used in experiment

Sample No.	Date prod.
Sample 1	26.09.2022
Sample 2	30.09.2022
Sample 3	17.10.2022
Sample 4	24.10.2022
Sample 5	31.10.2022
Sample 6	07.11.2022
Sample 7	21.11.2022

Production date refers to the date when cement mixture was created and filled into the molding construction to create a sample. Samples 1 – 6 including were used in the actual experimental work while sample seven was sacrificed for pre-experimental testing.

After the sample is extracted and put to storage, the modular molding construction is prepared for molding next sample. This is done by cleaning all the parts with ethanol. Residues from cement come off especially easy from the surfaces covered with transparent tape. For the places that are harder to clean like the filling holes in the top plate, a sharp blade of utility knife can be used to scrape off the cement residues. In the end those places are also wiped clean with ethanol and towel paper. Modular construction for molding concrete blocks is then assembled back again and is ready for another cement mixture.

First experiments performed on all six samples have been using 0.20kN of total compression load further referred to as total normal force. It means that each bolt was tightened to 0.10kN normal force. The next round of experiments was then performed at the same total initial normal force f 0.20kN. This was done to assess how successive experiments influence results. Final two rounds of experiments were performed at total initial normal forces of 0.10kN and 0.30kN. Meaning that initial loads on each of two bolts were 0.05kN for total initial force of 0.10kN and 0.15kN for the final round with total initial force of 0.30kN.

3.1.4 Experimental procedure for pushout tests on the rectangular assembly with sliding plate

This section describes experimental procedure for pushout tests on the rectangular assembly, during which the sliding plate confined between two concrete blocks of the sample has been pushed down using universal test machine MTS Criterion C45.

Procedure is started by taking the concrete sample outside of the storage container filled with water. All the tests were performed on the dry samples. So the sample to be tested was taken out of the water, dried with the paper towel and put aside in a dry place to dry out while the remaining pre experimental procedures were carried out. Important to note that a special care must be taken when handling sample as concrete is fragile and can crack if mishandled and dropped on the floor for an instance. Also, the surface of concrete blocks of the sample that were in contact with the sliding plate during the molding procedure should not be touched with fingers. This is done to avoid contamination of the surface where all impact is going to take place as that may alter experimental results.

Next step is preparation of the sliding plate. Both impact surfaces of sliding plate, that will be in a contact with concrete blocks during experiment, must be treated with same medium grit abrasive pad. Procedures are similar to the ones described earlier for roughness measurements and molding concrete blocks. Surfaces of sliding plate must be polished every time before each experiment. Figure 82 is summarizing these procedures in six steps. If the plate was used previously and has

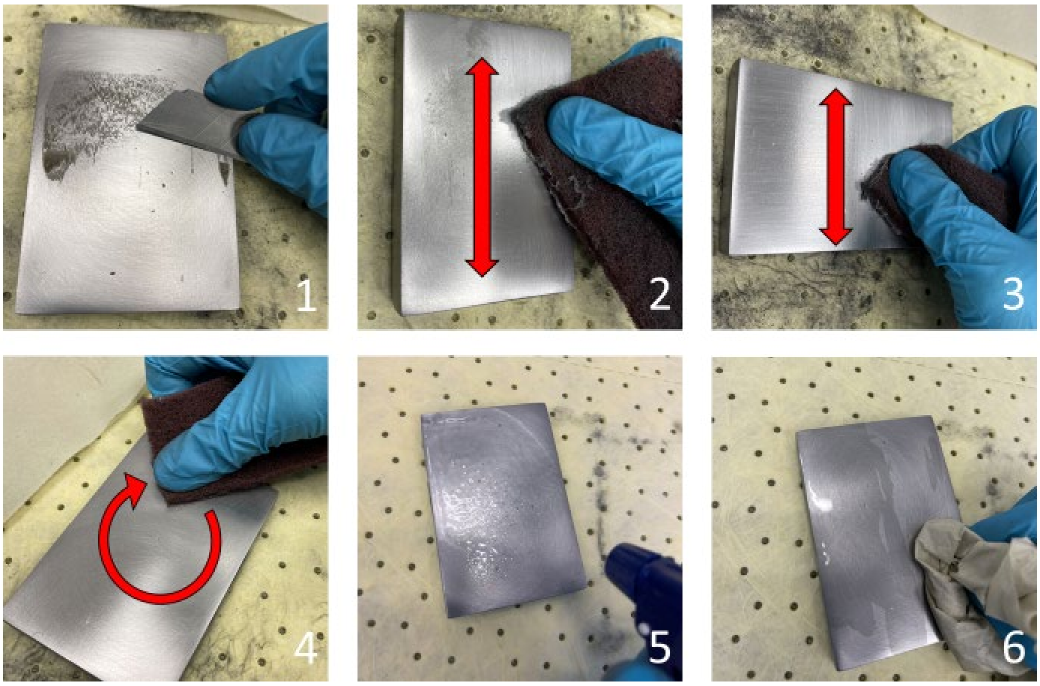


Figure 82: Treating surfaces of contaminated sliding plate with medium abrasive sheet, stepwise instructions

residues from the previous sample attached to its walls then a sharp blade of utility knife should be used first to scrape away thick layers of this residue. Steps 2 – 4 depictured in figure 82 are showing procedures of polishing surfaces of sliding plate with abrasive sheet. Finally the plate is cleaned with 85% ethanol mixture and dried with paper towels. The sliding plate is now ready for experiment and is set aside along with sample.

Now electrical assembly for compression washer load cells described in section 2.3, can be prepared. Figure 83 shows how electrical assembly looks when it is packed up for storage and transportation.

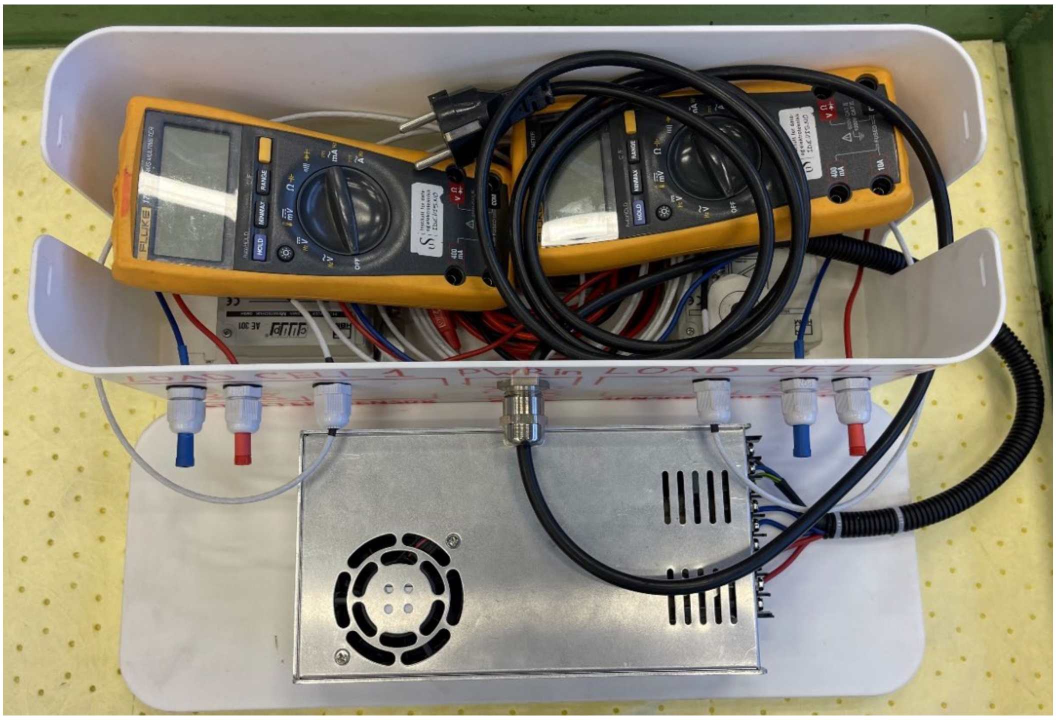


Figure 83: Electrical assembly for compression washer load cells in packed up condition

Both multimeters, both sensors, multimeter test leads and power cable are stored inside the plastic container under the lid. Container is placed on the trolley table and pushed next to the MTS machine. This is done as the sensor cables are only 1.5m long and load cells will have to go inside the cabinet of MTS machine. The contents of the box were emptied out. What is left inside the box is only both measuring amplifiers that are attached to the bottom of it and wiring. The lid of the box is then closed, and power cable is connected to 240V electricity means in the lab. Both Fluke 179 multimeters were then connected to AE 301 measuring amplifiers with banana plug type test leads through their marked terminals on the outside of electric box. Both multimeters are then set up to measure the DC voltage. Some voltage readings are showing the voltage of load cells that are not under any compression load yet (Figure 84). Sticker on the figure 84 is showing pre calculated voltage that will give chosen value of compression load for each cell.

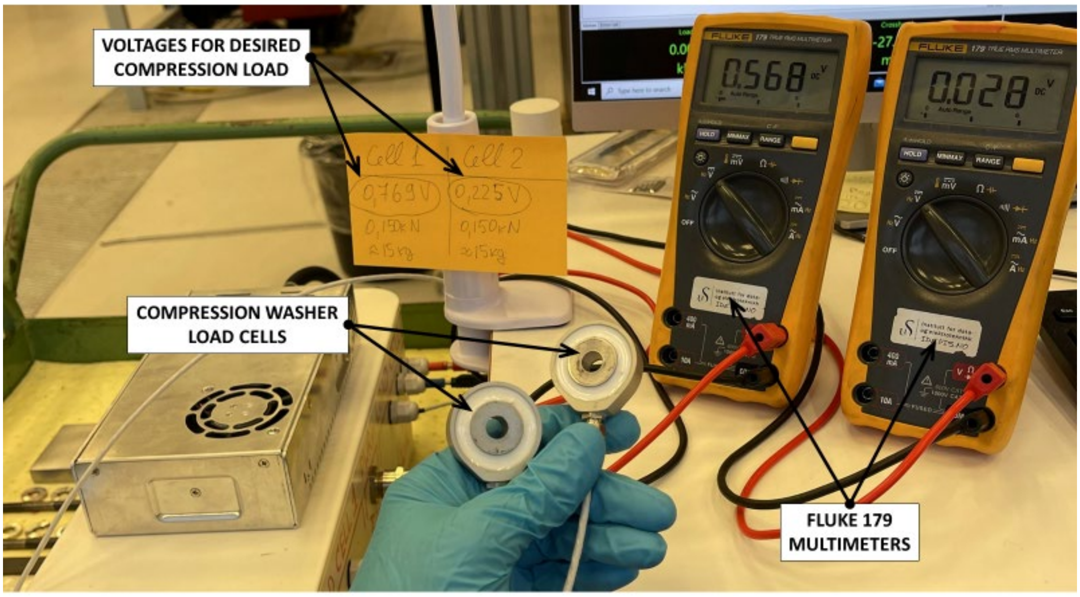


Figure 84: Multimeter setup for measuring ouput DC voltage form the compression washer load cells

Figure 85 shows all the parts needed to assemble rectangular construction for the pushout test. Assembly process was started from the ‘base’ that is the lower part of the construction serving as a fundament. Load cells were then attached on the bolts with the washers going from both sides as

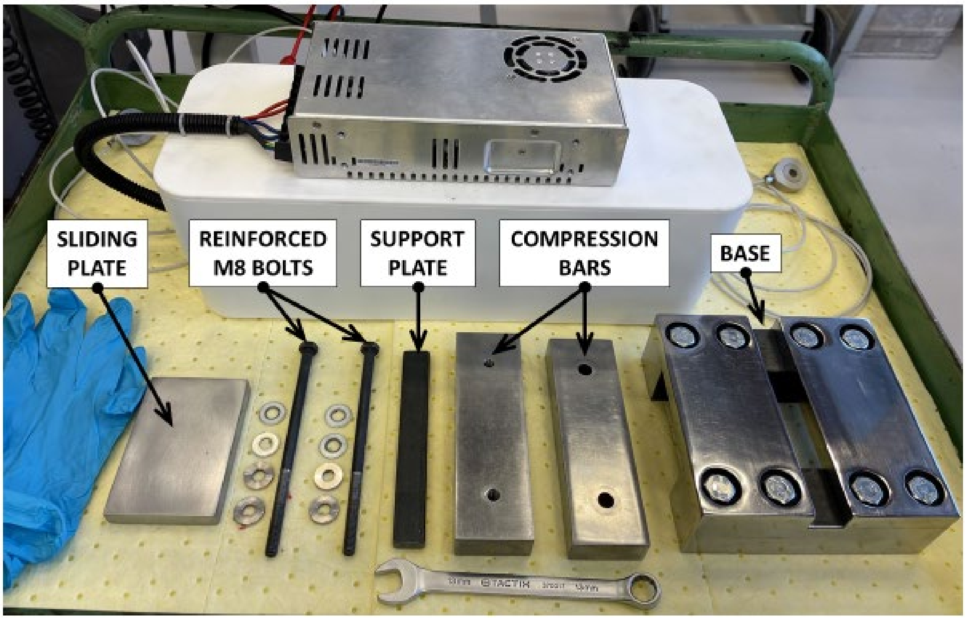


Figure 85: Parts for assembling rectangular construction for the pushout test

was illustrated in figure 56 in section 2.3. Construction called ‘vice’ is then assembled on the top of the base as described in section 2.2. Reinforced M8 bolts with washer load cells are first going through compression bar with larger holes and then are screwed inside another compression bar that has threads as shown on figure 86.

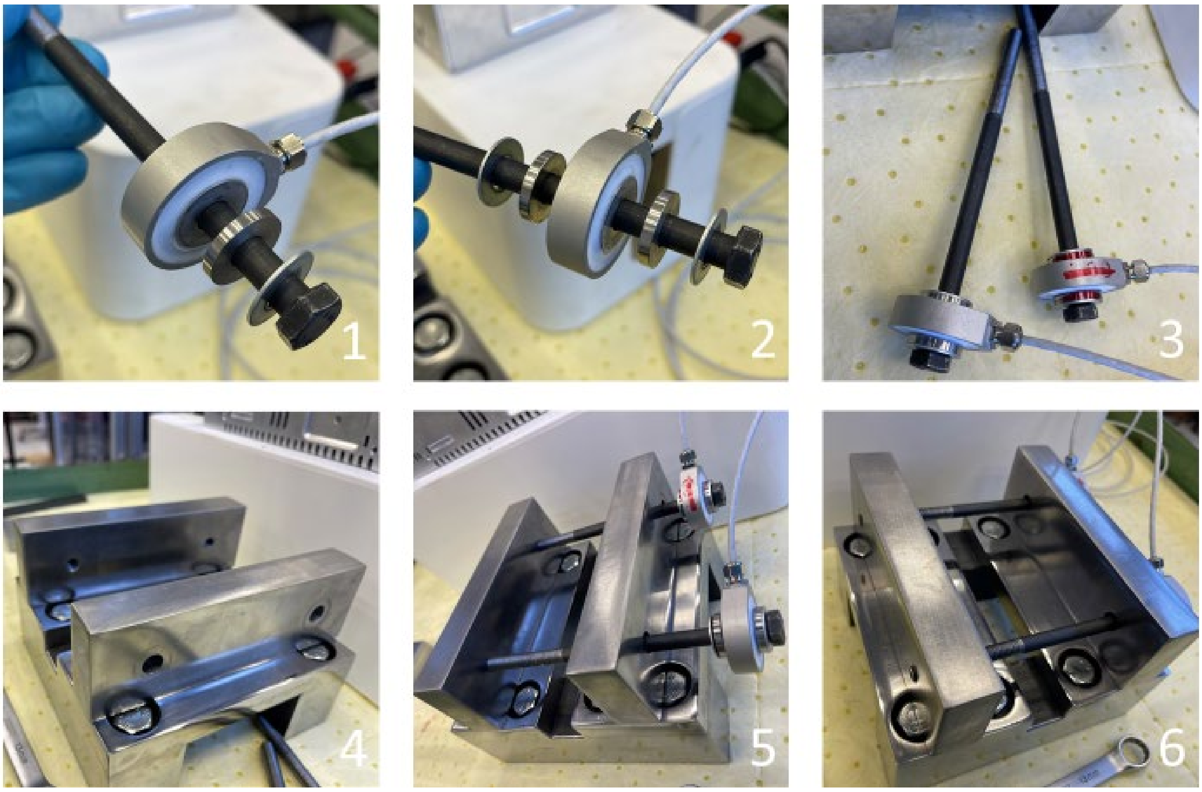


Figure 86: Stepwise assembly of vice

Bolts should not be sticking out of threaded compression bar as can be seen on step 6 in figure 86. When the vice is assembled, result should look as shown on the figure 87. It is important that vice is positioned in a such way that compression bars are being parallel to the longest side of rectangular hole in the middle of the base.

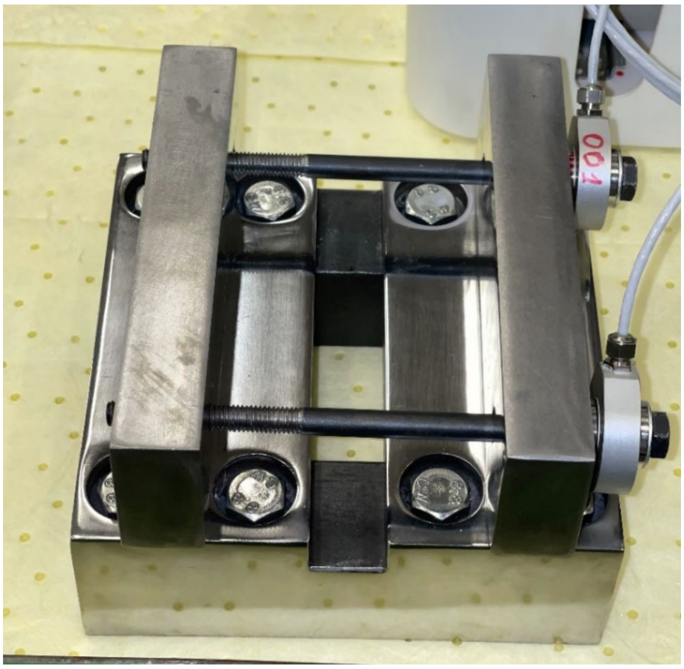


Figure 87: Assembled vice resting on the top of the base

Thin support steel plate is then placed the middle groove of the base and a sliding steel plate on the top of it as shown on the figure 88. This support plate helps during assembly process as it aligns sliding steel plate perpendicularly to the base and prevents it from dropping through the hole at the base.

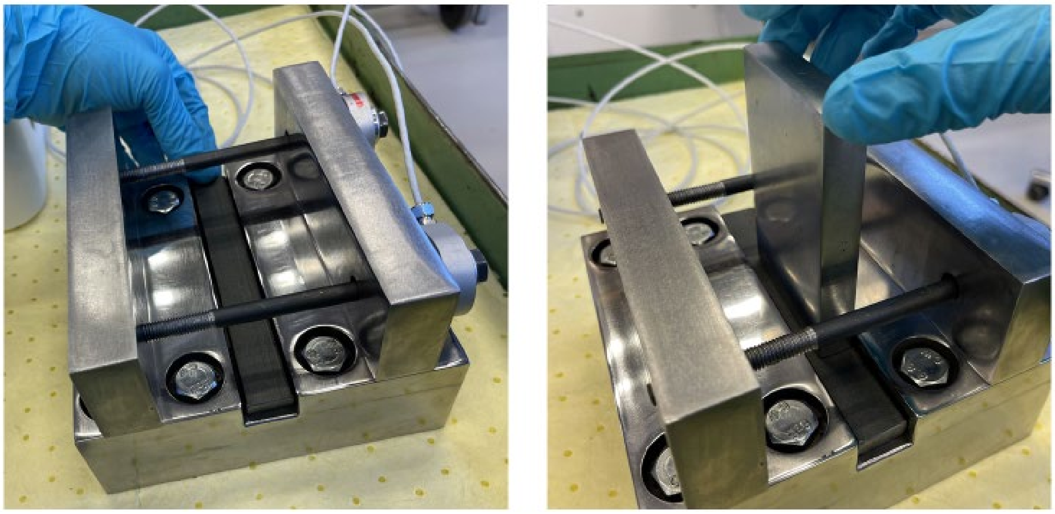


Figure 88: Mounting the sliding plate

Then cement blocks are placed on the base, leaving sliding steel plate in between them as shown on the figure 89 steps 1 - 2. 13mm wrench is used to tighten bolts (figure 89 step 3) until multimeters are showing the target voltage. Bolts are tightened gradually one after another to make sure that compression bars are kept parallel to each other, and compression load is evenly distributed. Afterthe vice is tightened and sliding plate is compressed in between the concrete blocks of sample, the support plate can be removed (Figure 89 step 4).

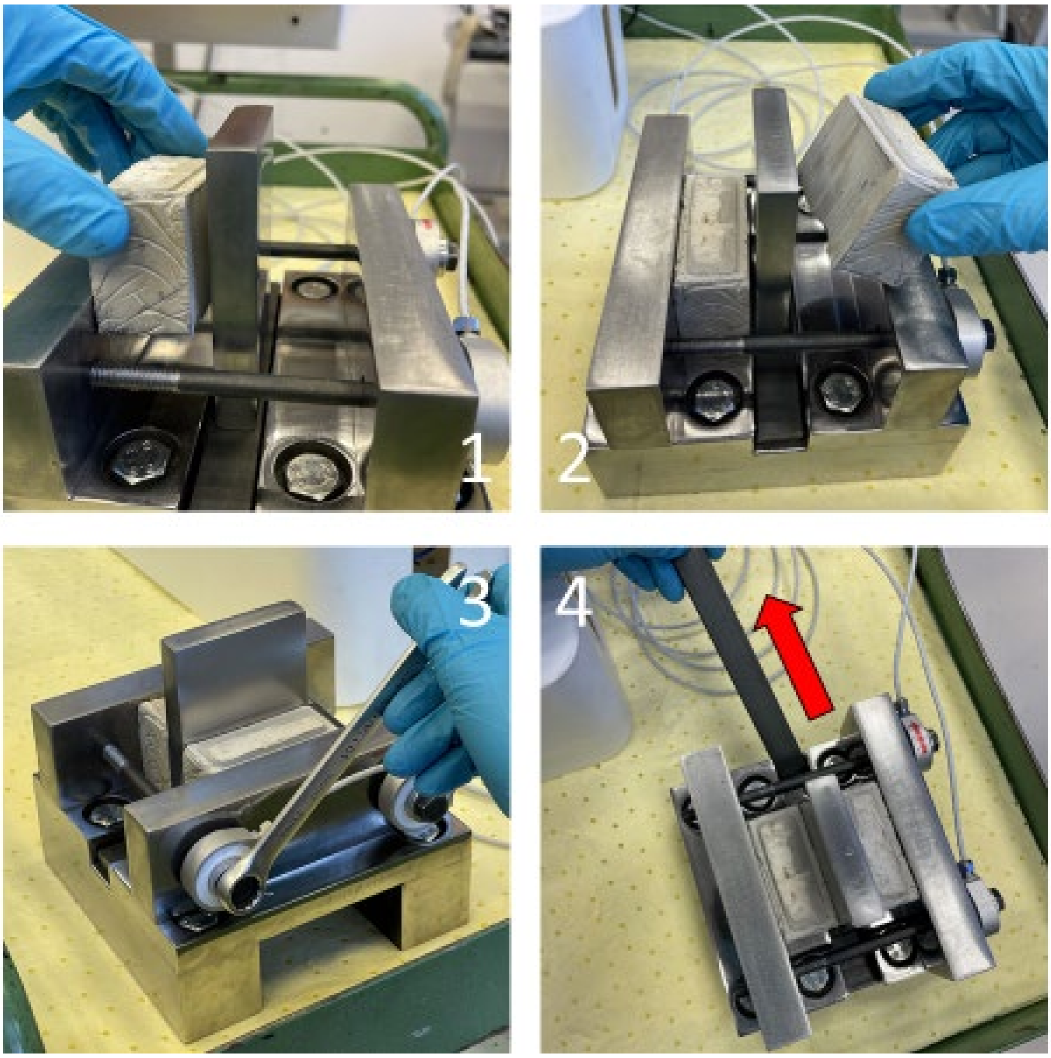


Figure 89: Inserting concrete blocks (steps 1-2), tightening bolts (step 3) and removing support plate (step 4)

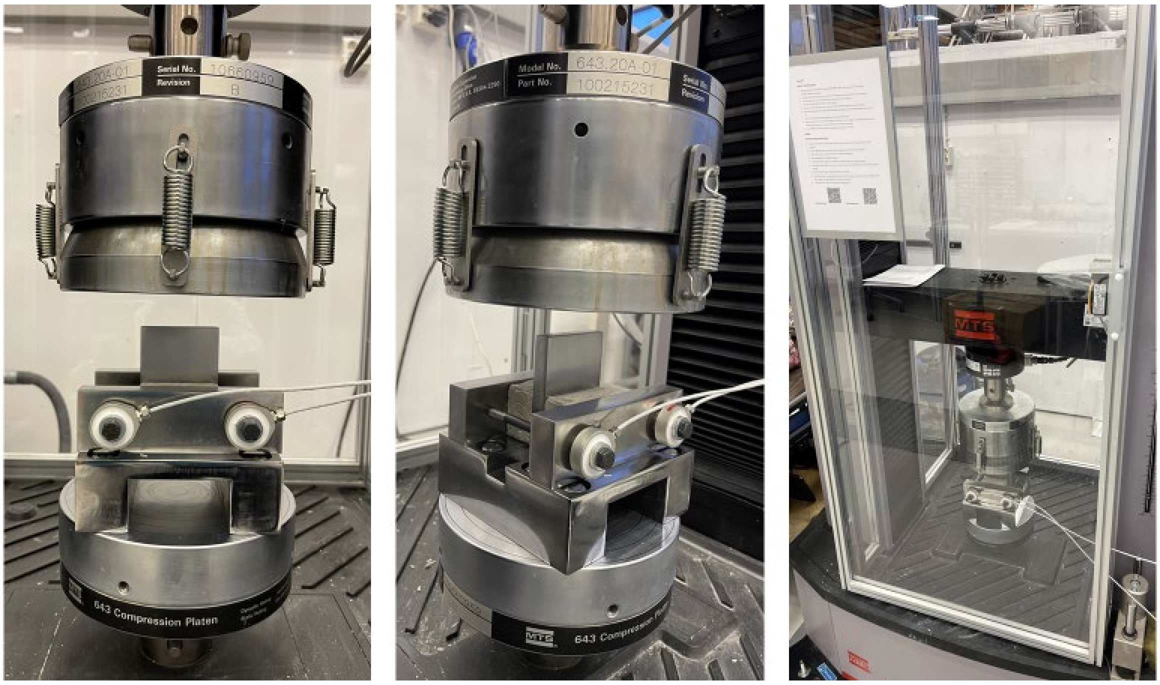


Figure 90: Rectangular pushout construction placed inside the cabinet of MTS machine

A platform inside the cabinet of MTS machine is cleaned with 85% ethanol mixture and wiped off with paper towel. Then the whole rectangular pushout assembly is placed inside the cabinet of machine and centered in the middle of the platform as shown on figure 90. The door of the cabinet is then closed.

Afterwards the compression piston position is adjusted using up and down buttons on the control unit of MTS machine and a wheel for more finer adjustments (Figure 91). Height is adjusted in a such way to have the smallest gap possible between the piston head and the top of the sliding plate.

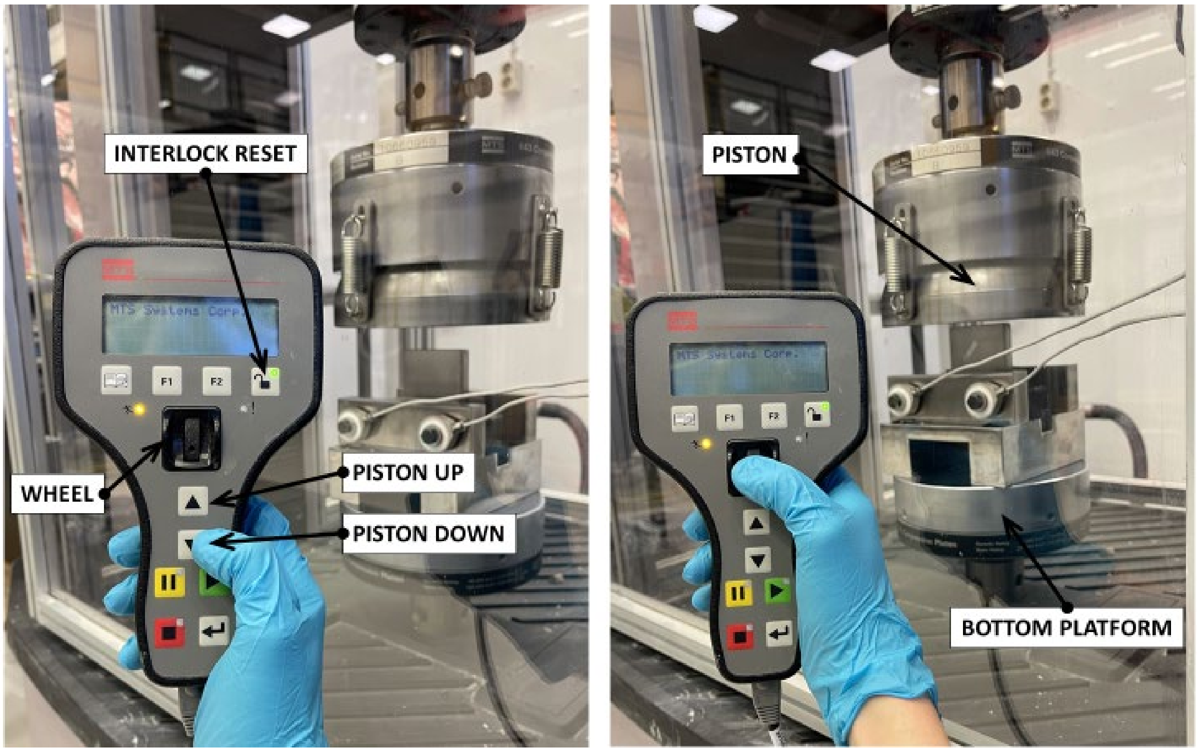


Figure 91: Compression piston head position adjustment using control unit of MTS machine

The gap between the piston head and sliding plate is adjusted to be the smallest possible in order to save time as the piston moves with the velocity of 1mm per minute and if the gap is huge, it will take a lot of time before piston head reaches the sliding plate. In order to use control unit of MTS machine, interlock reset button should be pressed until it lights green.

When control of the machine is passed over to the computer, the interlock button must be pressed so the green light goes off. Pattern for the displacement test was opened in the MTS Test Suite software. On the first page the main parameters for the machine are displaced. Data acquisition rate is kept 20Hz, velocity of the piston head is kept at 1mm per minute, preload speed is also kept at 1mm per minute and preload was set to 100N. At the bottom of the screen are represented three variables: load [kN], crosshead [mm] and time [s], showing their values in real life. Load shown is the load exerted by the piston on the sliding plate as it will be pushed down between concrete blocks with constant velocity. Crosshead is showing the displacement of the piston head and time is showing the elapsed time from the start of experiment. Load signal is reset from the computer before the start of experiment.

Before the experiment can be started, an iphone has been mounted on the stand to video record the values of load, crosshead and time from the monitor and voltage readings from both multimeters simultaneously as shown on the figure 92. Video recording on the phone was started and right after

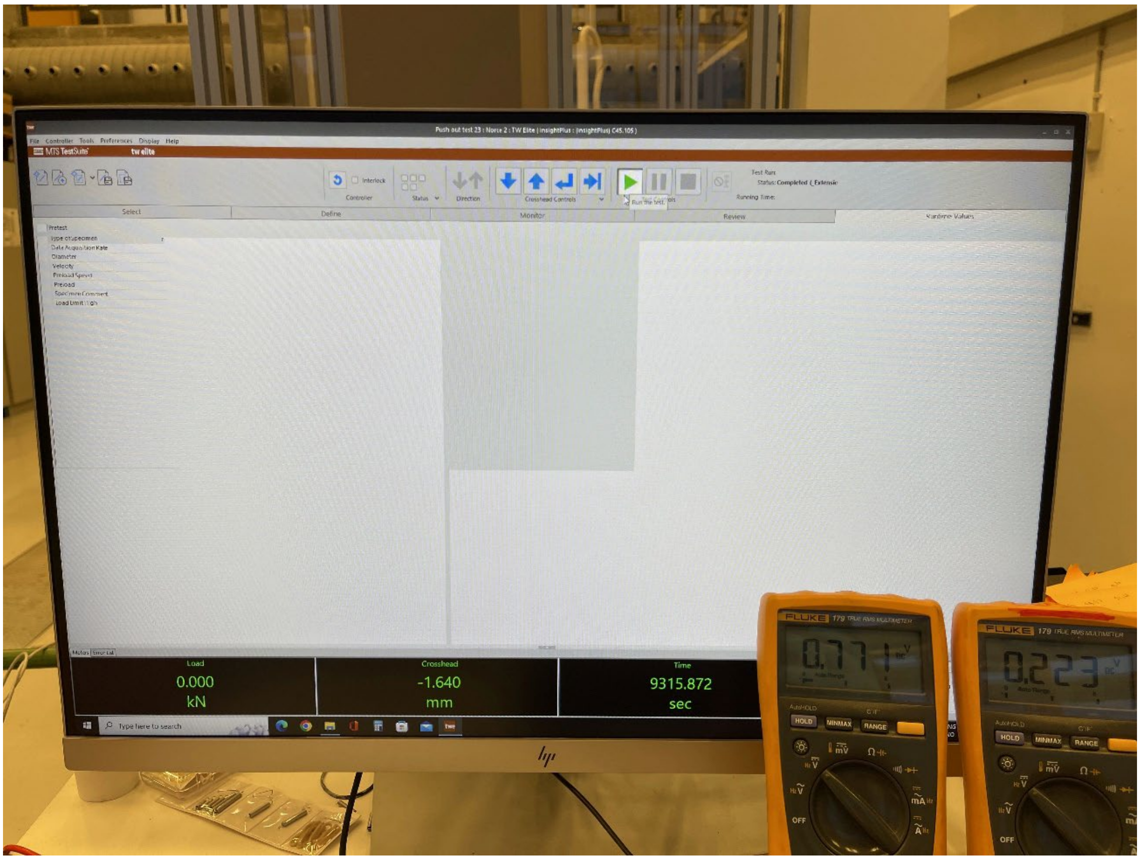


Figure 92: A view that is captured by the camera of an iphone where load, crosshead, time and voltage from both cells were recorded simultaneously

Pushout procedure was initiated as well. Piston starts to slowly move down with 1mm per minute. As the gap becomes smaller and surface of the piston touches the surface of the sliding plate, the load values start to climb up. When the preload of 0.1kN is reached, the values of time and crosshead are zeroed and start counting from there. Figure 93 is showing a screenshot from the video taken during the actual experiment.

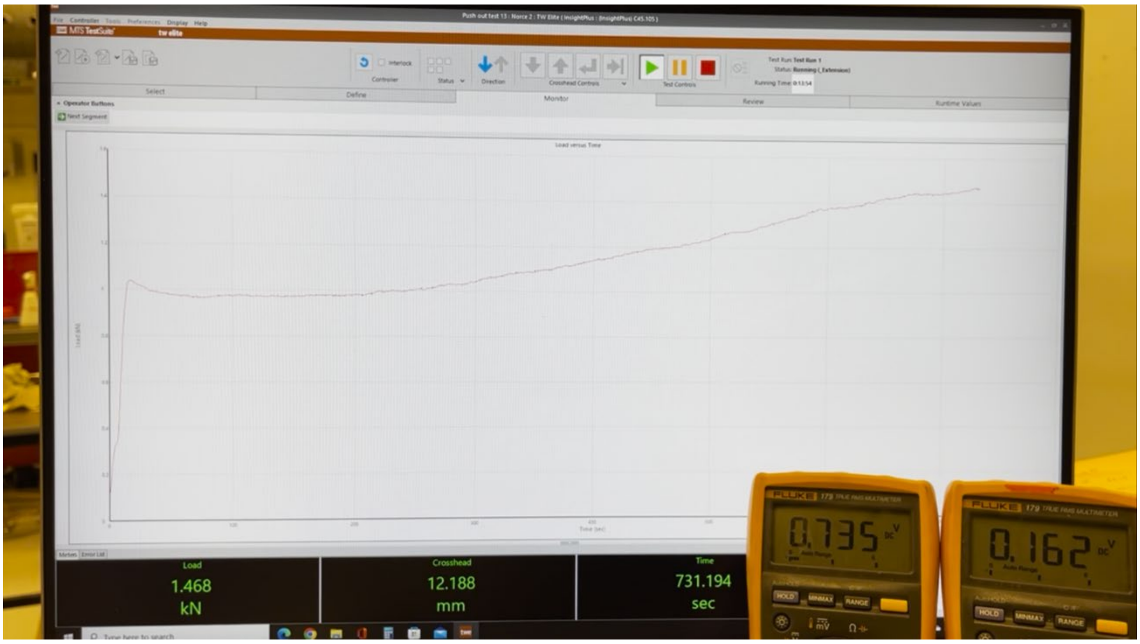


Figure 93: Screenshot from the video taken during the pushout test with sample 1

The duration of experiment is 30 minutes and during that time the sliding plate is displaced down 30mm. Experiment must be stopped manually as the given time has elapsed. Video recording is also stopped together with experiment and saved to be reviewed later. Piston automatically returns to its original position. Doors of the cabinet are then opened and assembly with the sample can be taken out. Now the reinforced bolts can be loosened, and the sample taken out, inspected and returned back to its storage container filled with water. Experiment can now continue with the next sample.

After the pushout tests on the rectangular assembly with sliding plate were finished, all the samples were carefully stored back into their storage containers, ready to be used in the next experiment that was conventional friction test on an inclined plane described in the next section.

3.2 Conventional friction tests on an inclined plane

Conventional friction test on an inclined plane, used to determine friction coefficient was described in section 1.1.1. Figure 94 shows the visual representation of equipment used for this type of test. More detailed figure 67 can be reviewed in section 2.4. Samples used are the same concrete blocks

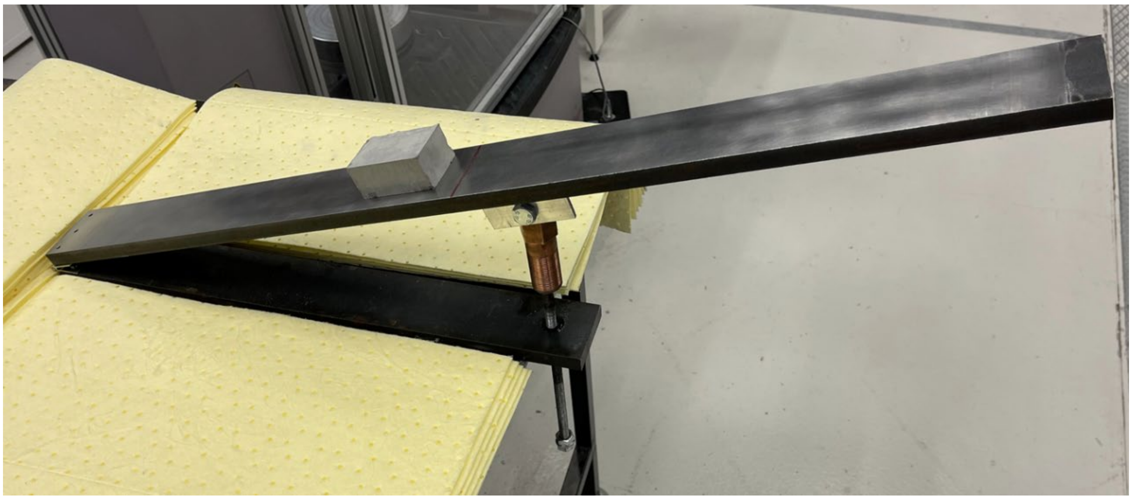


Figure 94: Construction for conventional friction experiment, visual representation

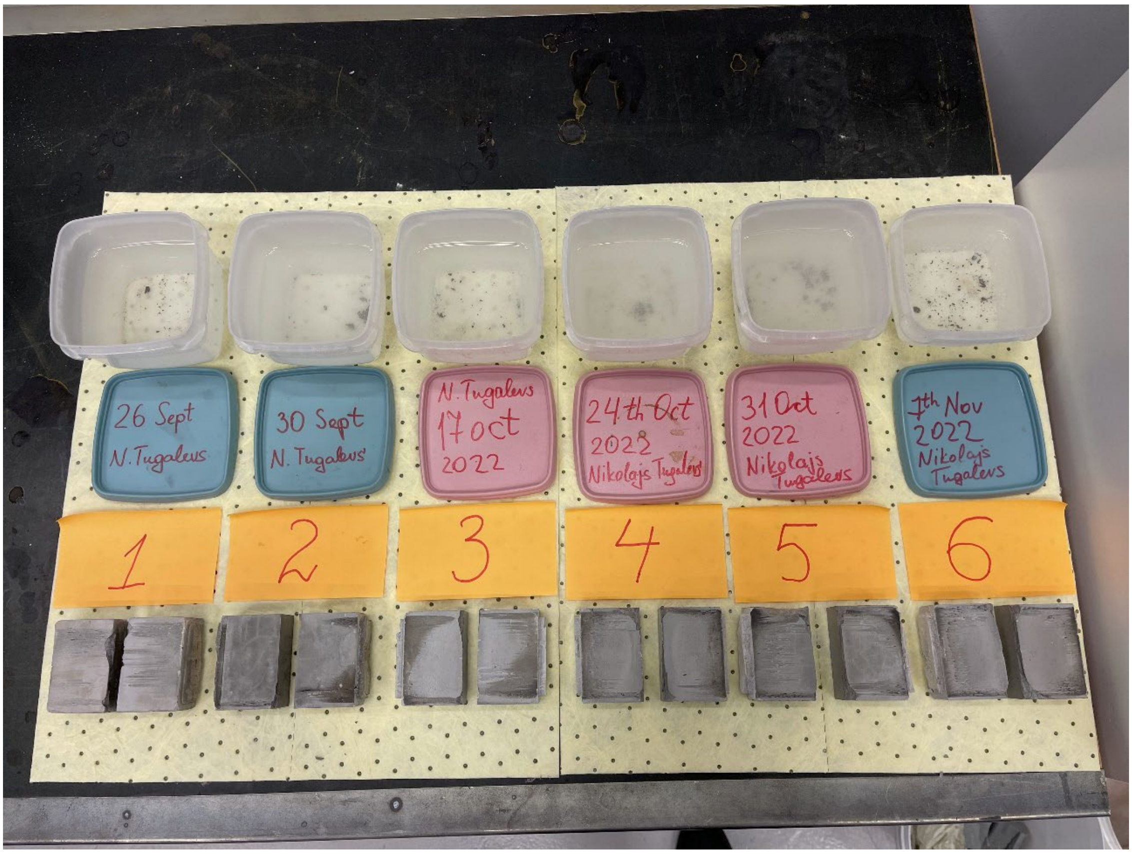


Figure 95: Pairs of concrete sample blocks from rectangular pushout test now used in conventional friction test

from the previous experiment (Figure 95). Some preparation needs to be done before the experiment can start. Surface of the inclined plate was polished with medium grit abrasive sheet in the same way as sliding plate that is described in section 3.1.2. First inclined plate was polished lengthwise along the longest side, then then thwartwise and finally in circular motion. After polishing process was done, roughness measurements of the polished surface were taken. Inclined plate is 90 cm long. Five roughness measurements were taken around three places on the plate as marked on figure 96. Points where the probe of roughness tester was placed are marked as red dots on the figure 96. Each group of five measurement points are located in the middle of the plate at 45cm mark and on the sides at 20 and 70cm marks. Results are summarized in the table 5 of section 4.2.

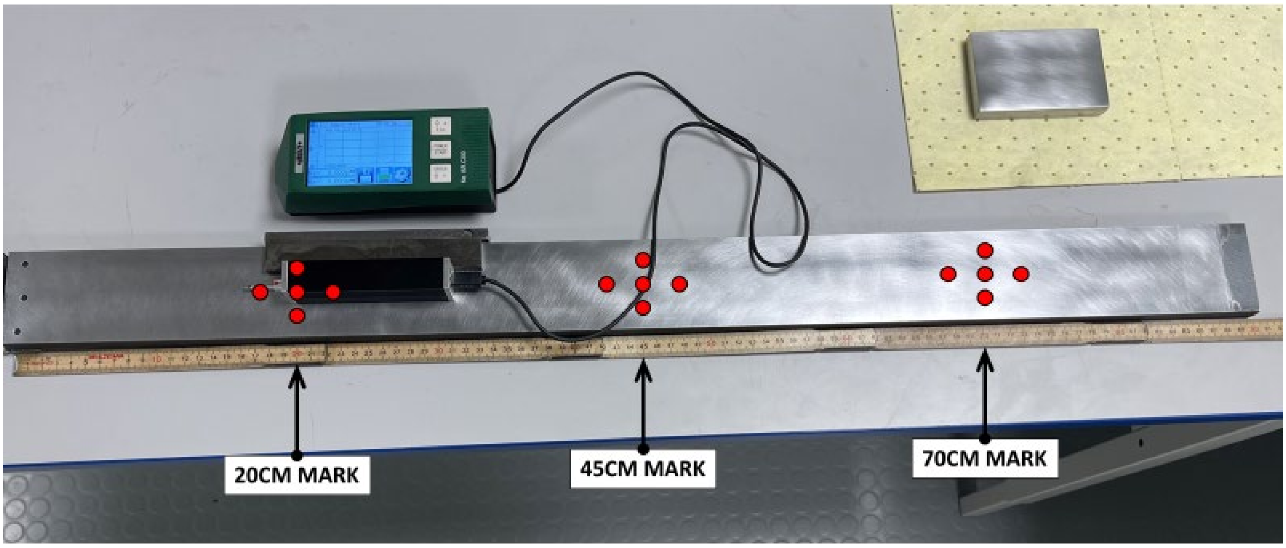


Figure 96: Roughness measurements of inclined plane taken around three marks of 20, 45 and 70cm

After roughness measurements are done the conventional friction test can be started. It consists of two parts. In the first part static friction coefficient was measured and in the second one dynamic was measured. Friction coefficient can be calculated directly from an angle ‘α’ between base and incline plates.

First power screwdriver was used to lower an incline plate. It was lowered to a such level that the concrete block of sample is laying stationary on its surface. Sample is laying with the side impacted by sliding plate facing downwards so that it is in a contact with polished surface of inclined plate. Then using the power screwdriver, the inclined plane was lifted until the sample begins to slide. At this point drill was stopped and the angle ‘a’ was estimated by measuring the lengths of hypothenuse (Figure 97) and opposite cathetus (Figure 98) of the right-angle triangle.

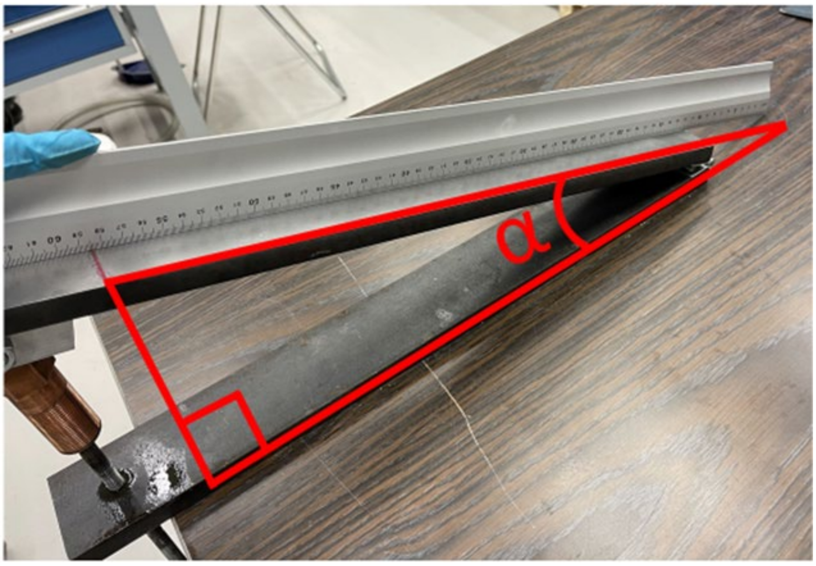


Figure 97: Measuring length of hypothenuse during conventional friction test

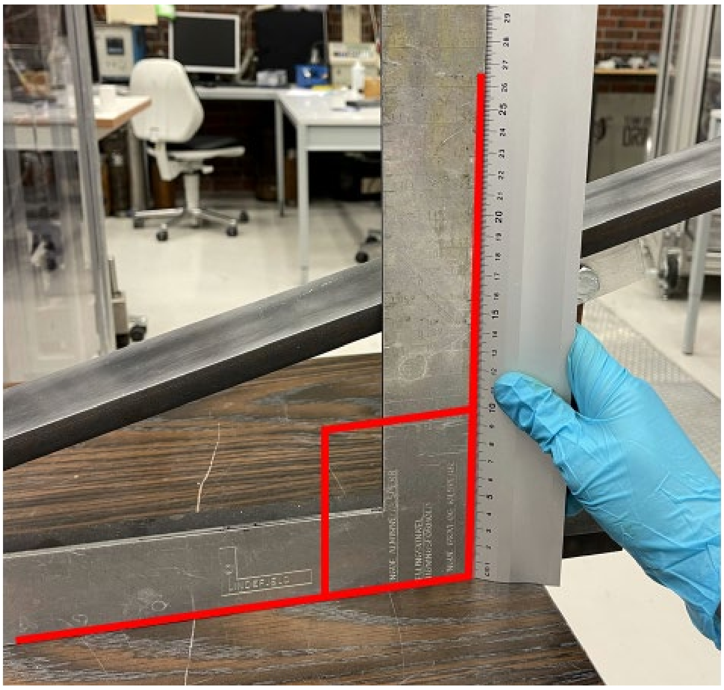


Figure 98: Measuring length of opposite cathetus during conventional friction test

Red mark on the inclined plane was serving as the reference when taking measurements. Each sample consists of two concrete blocks. Two blocks for one of the six samples were tested three times each, giving 36 experimental runs in total. All the results from the test are summarized in data table 20 of section 4.4. As the block is sliding down the inclined plate it is introducing tiny scratches in the plate that are altering future measurements. Therefore, the surface was polished with abrasive pad every time between switching blocks in the same manner as described earlier.

Procedure for the second part of experiment where the dynamic friction coefficient is being investigated is almost identical to the procedure of the first part with a small remark. This time the inclined plate was started from the higher position at which sample starts to slide instantly as soon as it was released to the surface of inclined plane. The plate has been lowered slowly while the sample was sliding until the sample breaks and remains stationary on the surface of inclined plane. Lengths of hypothenuse and opposite cathetus are then taken in the same manner as for the first part. The results are then summarized in the data table 21 of section 4.4.

4. Data collection and processing

4.1 Calibration of compression washer load cells

Following tables 2 – 3 are showing the data collected during the calibration of compression washer load cells in the universal testing machine Zwick/Roell ProLine. Procedure is described in section 3.1.1. Data table 2 shows applied load [kN] vs measured voltage [V] for load cell 1. Data table 3 shows applied load [kN] vs measured voltage [V] for load cell 2.

Table 2: Applied load [kN] vs measured voltage [V] vs for compression washer load cell 1

Compression washer load cell 1					
Preset load [kN]	Voltage measured [V]				
	Test 1	Test 2	Test 3	Test 4	Test 5
0.0	0.556	0.564	0.565	0.565	0.565
0.5	1.058	1.340	1.294	1.288	1.281
1.0	1.690	1.994	1.895	1.884	1.873
1.5	2.331	2.526	2.380	2.365	2.349
2.0	2.938	2.910	2.769	2.751	2.731
2.5	3.321	3.151	3.046	3.027	3.010
3.0	3.569	3.333	3.294	3.265	3.244
Success:	No	No	Yes	Yes	Yes

Table 3: Applied load [kN] vs measured voltage [V] vs for compression washer load cell 2

Compression washer load cell 2					
Preset load [kN]	Voltage measured [V]				
	Test 1	Test 2	Test 3	Test 4	Test 5
0.0	0.018	0.029	0.029	0.029	0.029
0.5	0.498	0.614	0.643	0.659	0.669
1.0	1.003	1.194	1.227	1.251	1.265
1.5	1.532	1.711	1.752	1.785	1.801
2.0	2.054	2.167	2.212	2.254	2.275
2.5	2.560	2.584	2.625	2.667	2.695
3.0	3.038	3.025	3.049	3.075	3.093
Success:	No	No	Yes	Yes	Yes

Preset voltage was chosen to be from 0.0 to 3.0kN with a step of 0.5kN. Test has been repeated five times for each cell and every time corresponding voltage was measured for each preset load. Values of the voltage at each preset load can be seen to converge from test 1 to test 5. During experiment washer load cells were attached to the base inside the cabinet of universal testing machine using multi-purpose sticky tacks from the sides. Those multi-purpose sticky tacks resemble plasteline and can stick to the surfaces. Attached from the sides, they help to keep load cell plat on the base before it is compressed with applied load from the piston head of machine. Even though attached from the sides, some pieces of the tacks might have slightly gotten in between the flat surface of load cell and base of machine. During the compression tests that small amount of tacks has been squeezed out from there back to the sides. As universal testing machine has a very sensitive load cells it has picked that up. Therefore last three tests 3 – 5 were used in calculating the average voltage measured from load cells. Results for the average voltage for the last three tests for both cells are presented in the data table 4.

Table 4: Calibration data for compression washer load cells

Preset load [kN]	Average voltage [V]	
	Load cell 1	Load cell 2
0.0	0.565	0.029
0.5	1.288	0.657
1.0	1.884	1.248
1.5	2.365	1.779
2.0	2.750	2.247
2.5	3.028	2.662
3.0	3.268	3.072

Based on the data provided in table 4, two calibration curves of load vs measured voltage have been plotted one for each cell. Figure 99 and figure 100 represent calibration curves for compression washer load cells 1 and 2 respectively.

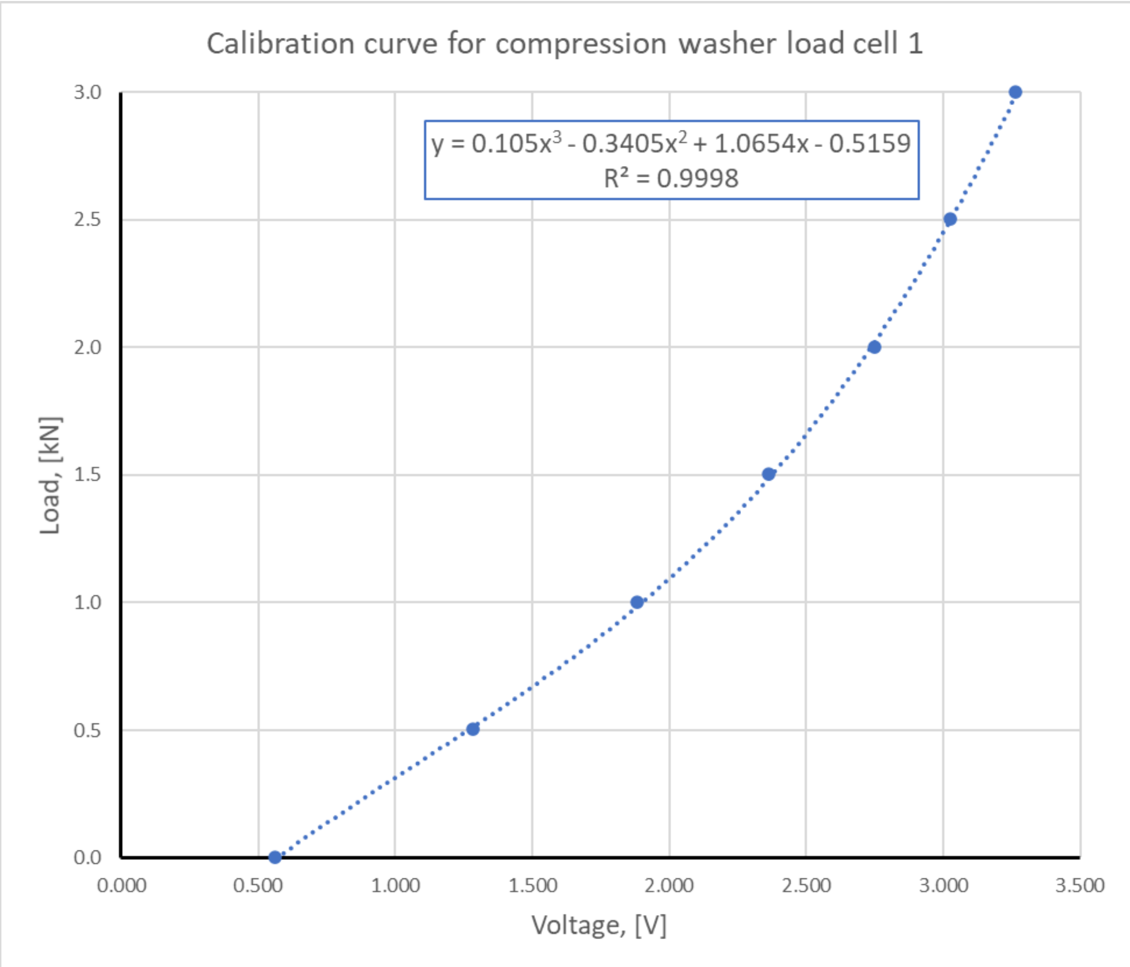


Figure 99: Calibration curve for compression washer load cell 1

Excel software has been used to generate best fit curve for the data points for both load cells. Equation of calibration curve is displayed on figure 99 and figure 100 for load cell 1 and 2 respectively.

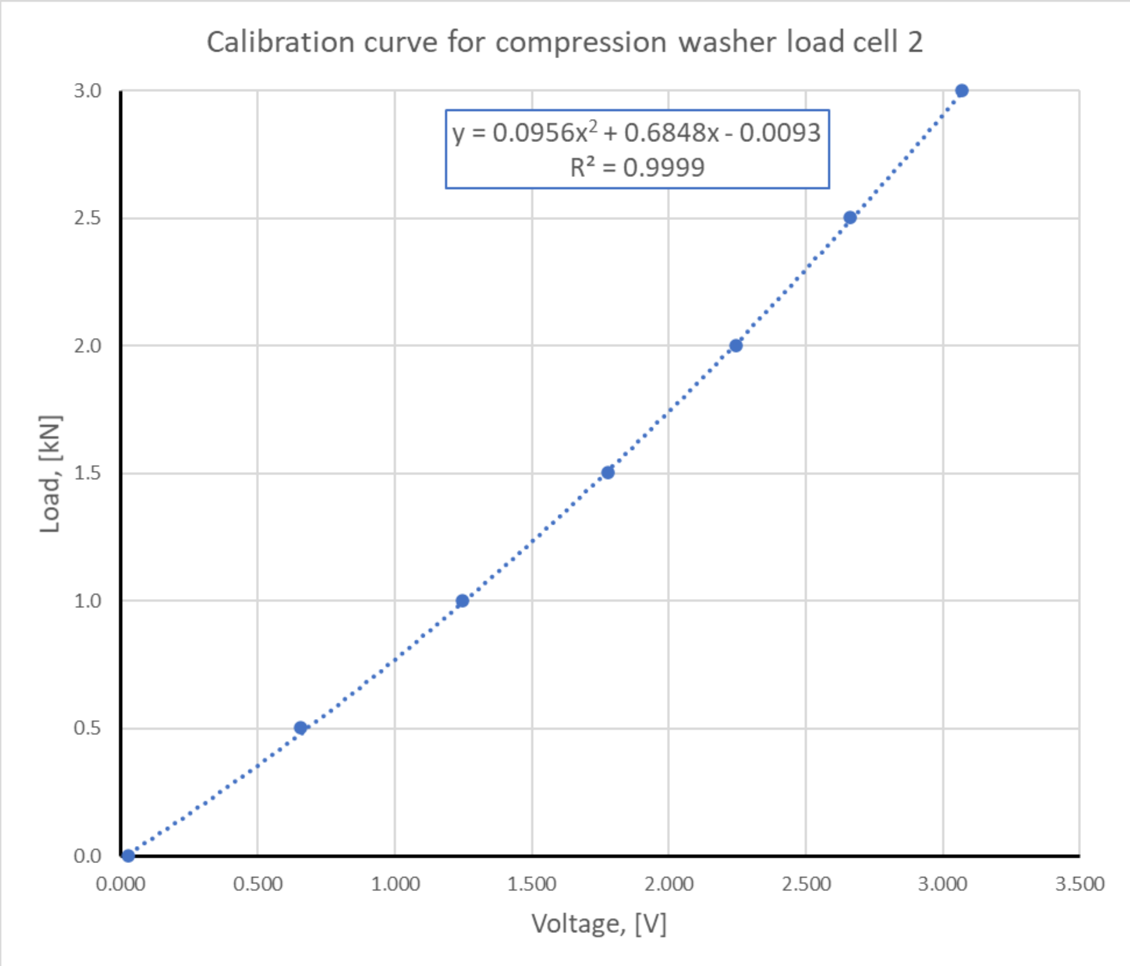


Figure 100: Calibration curve for compression washer load cell 2

For load cell 1, calibration curve is a polynomial of third degree:

$y = 0.105x^3 - 0.3405x^2 + 1.0654x - 0.5159$ equation 13

For load cell 2, calibration curve is a polynomial of second degree:

$y = 0.0956x^2 + 0.6848x - 0.0093$ equation 14

where y is load in [kN] and x is measured voltage in [V].

R^2 values for calibration curves of load cells are 0.9998 and 0.9999 for load cell 1 and 2 respectively. Both load and voltage values for load cells are provided with an accuracy up to three decimal spaces with ±0.001kN for load and ±0.001V for voltage measurements as those are measured digitally. When the R^2 value are rounded to three decimal spaces they become 1 for calibration curves of both cells. This means that calibration data fits 100% the regression model. In other words polynomial equations of calibration curves will provide 100% accurate values for the load based on the voltage input that is read from multimeters connected to the load cells. Equations 13 and 14 are futher used in this paper for interpreting the voltage [V] measurements to the load [kN] for compression washer load cells 1 and 2 respectively.

4.2 Results from roughness measurements on an inclined plane and sliding plate

Table 5: Roughness measurements for inclined plane

roughness for inclined plate [µm]			
	20	45	70
1	0.240	0.294	0.178
2	0.197	0.254	0.197
3	0.212	0.185	0.145
4	0.222	0.159	0.167
5	0.157	0.216	0.160
mean	0.199		
STD	0.042		

Table 6: Roughness measurements for sliding plate

roughness for sliding plate [µm]		
	up	down
1	0.240	0.294
2	0.197	0.254
3	0.212	0.185
4	0.222	0.159
5	0.157	0.216
mean	0.214	
STD	0.042	

4.3 Results from pushout experiments on rectangular assembly

In this section are presented results that were collected during pushout tests on the rectangular assembly with sliding plate compressed in between the blocks of concrete sample. Six samples were used for experiments. Each sample has been tested four times. For the first two tests, initial normal force was set to 0.20kN total. For the third and fourth test it was adjusted to 0.10kN and 0.30kN respectively.

Normal force is the same as the horizontal load [kN] applied to the sliding plate in the vice that was the part of the rectangular construction for the pushout test. Normal force was applied by tightening reinforced bolts and picked up by compression washer load cells. Signal from load cells measured in volts was later converted into kN using the equations for calibration curves for both load cells, described in the previous section.

Total normal force is the sum of the normal forces coming from both load cells. Normal force was distributed equally between both cells so for the total normal force Ntotal of 0.20kN the force on each of two cells equals to 0.10kN. For Ntotal of 0.10kN and 0.30kN forces on each load cells are 0.05kN and 0.15kN respectively. The term initial total normal force is used when referring to the tests. This is because normal force at each load cell that is preset to a specific value of in the beginning of each test will vary during experiment. Therefore, initial total normal force is used to distinguish between tests. Data table 7 presents voltage for each load cell corresponding to initial total normal force of 0.20kN, 0.10kN and 0.30kN used in experiments.

Table 7: Voltages [V] for load cells corresponding to preset initial normal forces [kN] used in tests

Initial normal force [kN]		Corresponding voltage [V]	
For each load cell	Total	Load cell 1	Load cell 2
0.10	0.20	0.701	0.156
0.05	0.10	0.635	0.086
0.15	0.30	0.769	0.225

Following data tables 8 – 11 are representing the data collected for sample 1 during pushout tests on the rectangular assembly. Tables 8 and 9 are representing data collected from test 1 and 2 respectively when initial Ntotal = 0.20kN. Tables 10 and 11 are representing data collected from test 3 when initial Ntotal = 0.10kN and test 4 when initial Ntotal = 0.30kN respectively. Each table includes five measured variables. First three measured variables come from MTS machine:

- Load F in [kN] – force exerted by the press on sliding plate
- Displ. In [mm] – displacement of the sliding plate
- Time [s] – elapsed time during experiment

Next two measured variables are voltages of compression washer load cells, that were displayed on the screens of multimeters. All measured variables were retrieved from the video recordings. Recordings were opened in VLC media player and scrolled frame by frame. Displacement measurements were used as a reference for all measured variables. Data was retrieved for discrete displacement measurements from 0 to 30mm with a step of 1mm.

Table 8: Data acquired from rectangular pushout test on sample 1 at initial Ntotal=0.20kN, test 1

Sample 1, Ntotal = 0.20kN, Test 1										
No.	Load F [kN]	Displ. [mm]	Time [s]	Voltage [V]		Normal force N [kN]			mu
				Cell 1	Cell 2	Cell 1	Cell 2	Total	
1	0.103	0.00	0.073	0.713	0.171	0.109	0.111	0.219	0.235
2	0.975	1.00	60.024	0.718	0.143	0.112	0.091	0.203	2.402
3	0.975	2.00	119.966	0.711	0.139	0.107	0.088	0.195	2.501
4	0.981	3.00	180.000	0.709	0.137	0.106	0.086	0.192	2.554
5	0.999	4.00	240.009	0.708	0.136	0.105	0.086	0.191	2.621
6	1.046	5.00	299.953	0.708	0.136	0.105	0.086	0.191	2.744
7	1.098	6.00	359.915	0.710	0.137	0.106	0.086	0.193	2.848
8	1.157	7.00	420.023	0.713	0.140	0.109	0.088	0.197	2.935
9	1.214	8.00	480.011	0.717	0.142	0.112	0.090	0.202	3.012
10	1.286	9.00	540.004	0.720	0.146	0.114	0.093	0.207	3.113
11	1.371	10.00	599.992	0.726	0.152	0.118	0.097	0.215	3.184
12	1.423	11.00	659.950	0.730	0.157	0.121	0.101	0.222	3.208
13	1.459	12.00	719.890	0.734	0.160	0.124	0.103	0.227	3.215
14	1.506	13.00	779.966	0.739	0.166	0.128	0.107	0.235	3.206
15	1.573	14.00	839.906	0.747	0.173	0.134	0.112	0.246	3.200
16	1.559	15.00	900.006	0.754	0.179	0.139	0.116	0.255	3.055
17	1.604	16.00	959.977	0.755	0.183	0.140	0.119	0.259	3.099
18	1.611	17.00	1019.896	0.763	0.190	0.145	0.124	0.270	2.987
19	1.661	18.00	1079.939	0.762	0.194	0.145	0.127	0.272	3.055
20	1.701	19.00	1139.958	0.762	0.199	0.145	0.131	0.275	3.088
21	1.662	20.00	1199.910	0.768	0.206	0.149	0.136	0.285	2.917
22	1.722	21.00	1260.010	0.767	0.208	0.148	0.137	0.286	3.015
23	1.718	22.00	1319.971	0.772	0.215	0.152	0.142	0.294	2.919
24	1.691	23.00	1379.968	0.773	0.225	0.153	0.150	0.302	2.797
25	1.759	24.00	1439.967	0.772	0.224	0.152	0.149	0.301	2.923
26	1.790	25.00	1499.970	0.771	0.226	0.151	0.150	0.302	2.968
27	1.779	26.00	1559.998	0.775	0.232	0.154	0.155	0.309	2.880
28	1.829	27.00	1619.908	0.774	0.235	0.153	0.157	0.310	2.947
29	1.729	28.00	1679.994	0.840	0.333	0.201	0.229	0.430	2.009
30	1.139	29.00	1739.963	0.818	0.287	0.185	0.195	0.380	1.497
31	1.137	30.00	1799.970	0.817	0.282	0.185	0.191	0.376	1.512

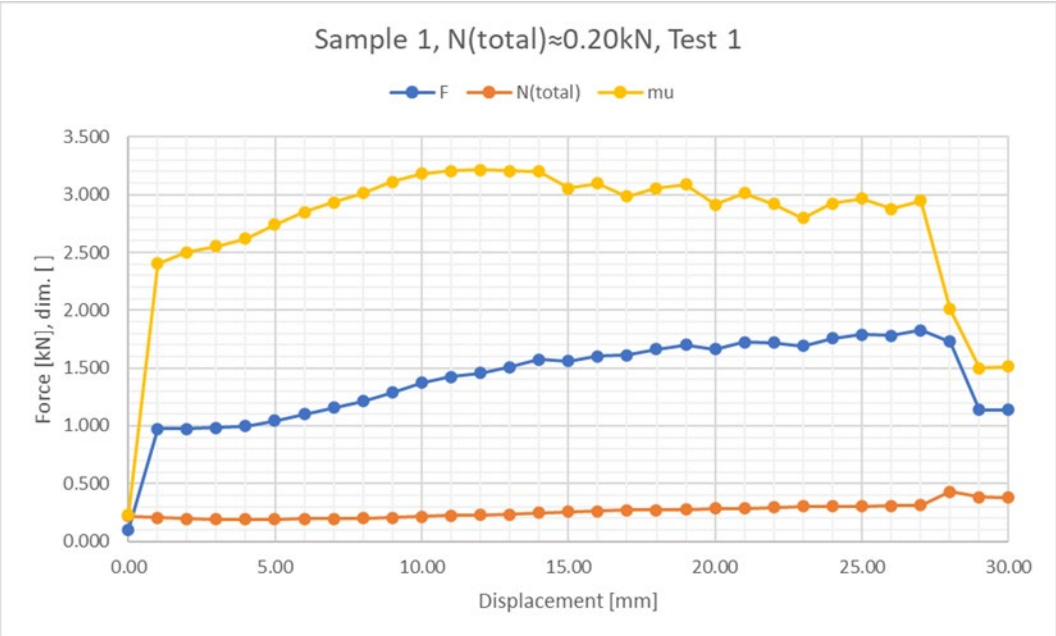


Figure 101: Sample 1, Ntotal=0.20kN, test 1, graph showing variation of F, Ntotal and mu vs displacement

Table 9: Data acquired from rectangular pushout test on sample 1 at initial Ntotal=0.20kN, test 2

Sample 1, Ntotal = 0.20kN, Test 2									
No.	Load F [kN]	Displ. [mm]	Time [s]	Voltage [V]		Normal force N [kN]			mu
				Cell 1	Cell 2	Cell 1	Cell 2	Total	
1	0.100	0.001	0.040	0.727	0.176	0.119	0.114	0.233	0.214
2	0.816	0.999	59.938	0.731	0.163	0.122	0.105	0.227	1.799
3	0.775	2.000	119.985	0.727	0.160	0.119	0.103	0.222	1.748
4	0.768	3.000	180.002	0.725	0.158	0.118	0.101	0.219	1.755
5	0.780	4.000	240.003	0.724	0.158	0.117	0.101	0.218	1.788
6	0.809	4.999	299.892	0.724	0.158	0.117	0.101	0.218	1.855
7	0.834	6.000	359.987	0.725	0.160	0.118	0.103	0.220	1.893
8	0.874	7.000	419.913	0.726	0.162	0.118	0.104	0.222	1.965
9	0.931	7.999	479.877	0.728	0.166	0.120	0.107	0.227	2.053
10	0.968	9.000	540.001	0.731	0.172	0.122	0.111	0.233	2.075
11	0.971	10.000	599.936	0.733	0.180	0.123	0.117	0.241	2.019
12	1.008	11.000	660.017	0.736	0.185	0.126	0.121	0.246	2.046
13	1.041	12.000	720.034	0.739	0.190	0.128	0.124	0.252	2.065
14	1.070	13.000	780.029	0.743	0.200	0.131	0.131	0.262	2.040
15	1.107	13.999	839.887	0.747	0.206	0.134	0.136	0.270	2.053
16	1.131	15.000	899.936	0.749	0.207	0.135	0.137	0.272	2.081
17	1.147	16.000	959.981	0.752	0.212	0.137	0.140	0.278	2.066
18	1.173	17.000	1019.973	0.755	0.219	0.140	0.145	0.285	2.059
19	1.192	18.000	1080.005	0.758	0.226	0.142	0.150	0.292	2.040
20	1.226	19.000	1139.981	0.759	0.227	0.142	0.151	0.294	2.088
21	1.255	19.999	1199.973	0.762	0.235	0.145	0.157	0.302	2.081
22	1.270	20.999	1259.899	0.763	0.237	0.145	0.158	0.304	2.090
23	1.253	22.000	1319.987	0.765	0.242	0.147	0.162	0.309	2.028
24	1.276	22.999	1379.954	0.767	0.248	0.148	0.166	0.315	2.027
25	1.269	24.000	1440.014	0.768	0.249	0.149	0.167	0.316	2.007
26	1.272	24.999	1499.896	0.768	0.249	0.149	0.167	0.316	2.011
27	1.292	26.000	1559.995	0.769	0.251	0.150	0.169	0.318	2.029
28	1.339	26.999	1619.890	0.771	0.254	0.151	0.171	0.322	2.079
29	1.349	27.999	1679.959	0.771	0.253	0.151	0.170	0.321	2.099
30	1.125	29.000	1739.993	0.788	0.271	0.164	0.183	0.347	1.622
31	1.182	30.000	1799.964	0.784	0.266	0.161	0.180	0.340	1.737

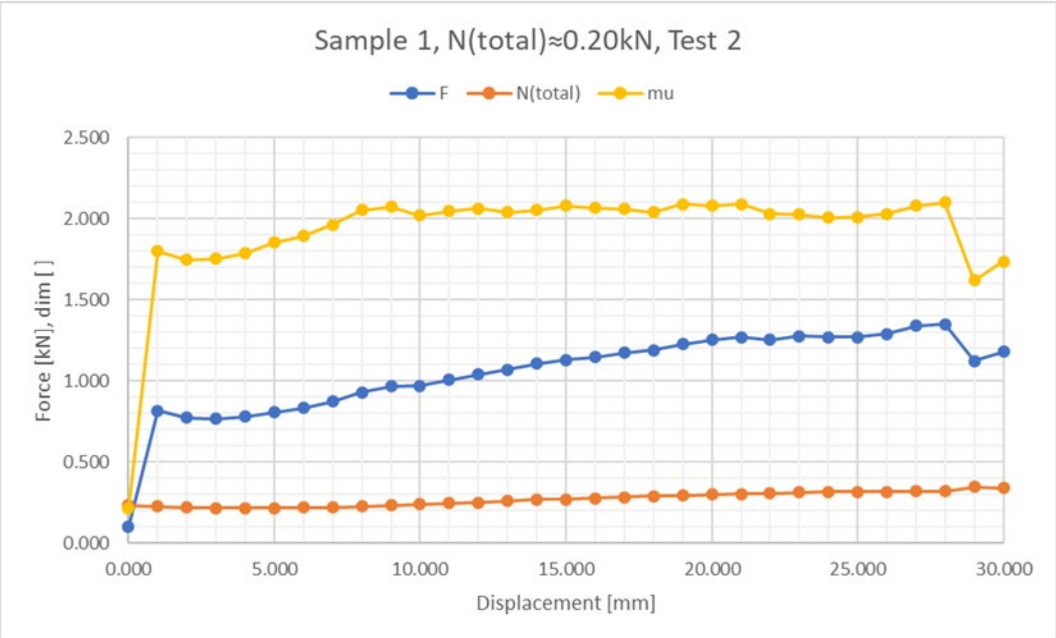


Figure 102: Sample 1, Ntotal=0.20kN, test 2, graph showing variation of F, Ntotal and mu vs displacement

Table 10: Data acquired from rectangular pushout test on sample 1 at initial Ntotal=0.10kN, test 3

Sample 1, Ntotal = 0.10kN, Test 3									
No.	Load F [kN]	Displ. [mm]	Time [s]	Voltage [V]		Normal force N [kN]			mu
				Cell 1	Cell 2	Cell 1	Cell 2	Total	
1	0.098	0.000	0.045	0.636	0.083	0.051	0.048	0.099	0.494
2	0.306	1.000	60.039	0.645	0.077	0.058	0.044	0.102	1.503
3	0.347	2.000	119.983	0.646	0.077	0.059	0.044	0.103	1.692
4	0.377	3.000	179.988	0.650	0.075	0.062	0.043	0.104	1.809
5	0.418	3.999	239.953	0.654	0.075	0.065	0.043	0.107	1.950
6	0.445	5.000	300.038	0.657	0.074	0.067	0.042	0.109	2.046
7	0.457	6.000	360.001	0.660	0.073	0.069	0.041	0.110	2.071
8	0.468	6.999	419.952	0.661	0.073	0.070	0.041	0.111	2.107
9	0.475	8.000	479.948	0.662	0.073	0.071	0.041	0.112	2.124
10	0.483	9.000	539.966	0.663	0.073	0.071	0.041	0.113	2.145
11	0.494	10.000	600.064	0.665	0.073	0.073	0.041	0.114	2.165
12	0.503	11.000	660.036	0.668	0.073	0.075	0.041	0.116	2.162
13	0.498	12.000	719.991	0.669	0.074	0.076	0.042	0.118	2.114
14	0.501	12.999	779.950	0.671	0.074	0.077	0.042	0.119	2.100
15	0.505	13.999	840.016	0.673	0.074	0.079	0.042	0.121	2.090
16	0.514	15.000	899.979	0.674	0.075	0.080	0.043	0.122	2.102
17	0.520	16.000	959.951	0.676	0.075	0.081	0.043	0.124	2.101
18	0.516	16.999	1019.839	0.677	0.075	0.082	0.043	0.124	2.072
19	0.521	17.999	1079.943	0.678	0.075	0.083	0.043	0.125	2.080
20	0.521	19.000	1139.996	0.679	0.076	0.083	0.043	0.127	2.056
21	0.529	20.000	1200.014	0.679	0.076	0.083	0.043	0.127	2.088
22	0.517	20.999	1259.963	0.679	0.076	0.083	0.043	0.127	2.040
23	0.502	21.999	1319.956	0.678	0.075	0.083	0.043	0.125	2.004
24	0.516	22.999	1379.988	0.679	0.075	0.083	0.043	0.126	2.048
25	0.530	23.999	1439.941	0.680	0.077	0.084	0.044	0.128	2.068
26	0.532	24.999	1499.947	0.681	0.078	0.085	0.045	0.130	2.053
27	0.544	26.000	1560.049	0.683	0.079	0.086	0.045	0.132	2.064
28	0.550	27.000	1619.940	0.684	0.080	0.087	0.046	0.133	2.064
29	0.563	28.000	1680.039	0.686	0.082	0.089	0.047	0.136	2.068
30	0.569	29.000	1739.934	0.687	0.084	0.089	0.049	0.138	2.058
31	0.580	30.000	1799.993	0.688	0.085	0.090	0.050	0.140	2.076

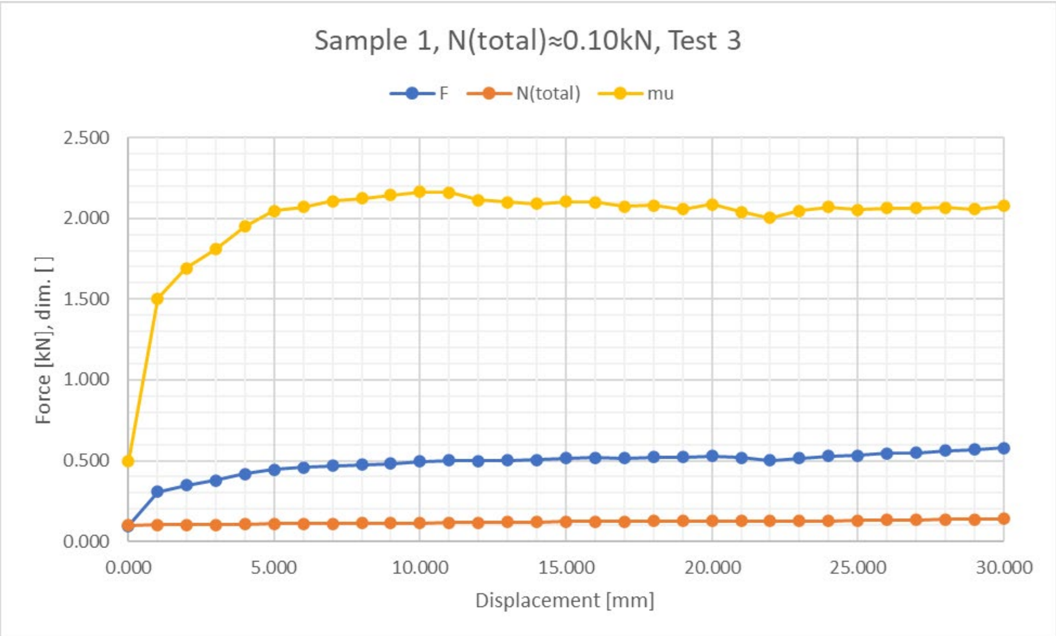


Figure 103: Sample 1, Ntotal=0.10kN, test 3, graph showing variation of F, Ntotal and mu vs displacement

Table 11: Data acquired from rectangular pushout test on sample 1 at initial Ntotal=0.30kN, test 4

Sample 1, Ntotal = 0.30kN, Test 4									
No.	Load F [kN]	Displ. [mm]	Time [s]	Voltage [V]		Normal force N [kN]			mu
				Cell 1	Cell 2	Cell 1	Cell 2	Total	
1	0.099	0.001	0.041	0.771	0.217	0.151	0.144	0.295	0.168
2	1.218	0.999	60.001	0.768	0.200	0.149	0.131	0.281	2.171
3	1.354	1.999	119.997	0.770	0.197	0.151	0.129	0.280	2.419
4	1.420	2.999	179.935	0.772	0.196	0.152	0.129	0.281	2.531
5	1.483	4.000	240.026	0.774	0.195	0.153	0.128	0.281	2.636
6	1.546	5.000	299.934	0.777	0.194	0.156	0.127	0.283	2.734
7	1.614	5.999	359.941	0.780	0.193	0.158	0.126	0.284	2.839
8	1.665	7.000	419.984	0.783	0.193	0.160	0.126	0.286	2.907
9	1.716	7.999	479.888	0.786	0.193	0.162	0.126	0.289	2.973
10	1.755	9.000	539.892	0.789	0.194	0.164	0.127	0.291	3.011
11	1.753	9.999	599.969	0.795	0.199	0.169	0.131	0.299	2.927
12	1.823	10.999	659.890	0.797	0.200	0.170	0.131	0.302	3.022
13	1.874	12.000	720.028	0.799	0.201	0.172	0.132	0.304	3.085
14	1.896	13.000	779.955	0.801	0.203	0.173	0.134	0.307	3.092
15	1.868	13.999	839.953	0.806	0.211	0.177	0.139	0.316	2.955
16	1.881	15.000	899.964	0.807	0.213	0.177	0.141	0.318	2.956
17	1.901	16.000	960.019	0.809	0.214	0.179	0.142	0.320	2.967
18	1.847	16.999	1019.943	0.811	0.220	0.180	0.146	0.326	2.831
19	1.886	18.000	1079.989	0.813	0.221	0.182	0.147	0.328	2.872
20	1.915	18.999	1139.962	0.814	0.222	0.182	0.147	0.330	2.903
21	1.920	20.000	1199.974	0.816	0.224	0.184	0.149	0.333	2.886
22	1.931	21.000	1260.001	0.816	0.225	0.184	0.150	0.333	2.896
23	1.935	21.999	1319.997	0.817	0.226	0.185	0.150	0.335	2.889
24	1.942	22.999	1379.950	0.818	0.227	0.185	0.151	0.336	2.887
25	1.924	23.999	1439.959	0.819	0.228	0.186	0.152	0.338	2.848
26	1.921	24.999	1499.895	0.820	0.229	0.187	0.153	0.339	2.832
27	1.929	26.000	1559.962	0.821	0.231	0.187	0.154	0.341	2.825
28	1.916	26.999	1619.914	0.822	0.232	0.188	0.155	0.343	2.794
29	1.958	28.000	1679.977	0.822	0.235	0.188	0.157	0.345	2.838
30	2.004	29.000	1740.018	0.823	0.237	0.189	0.158	0.347	2.886
31	1.987	29.999	1799.958	0.825	0.239	0.190	0.160	0.350	2.838

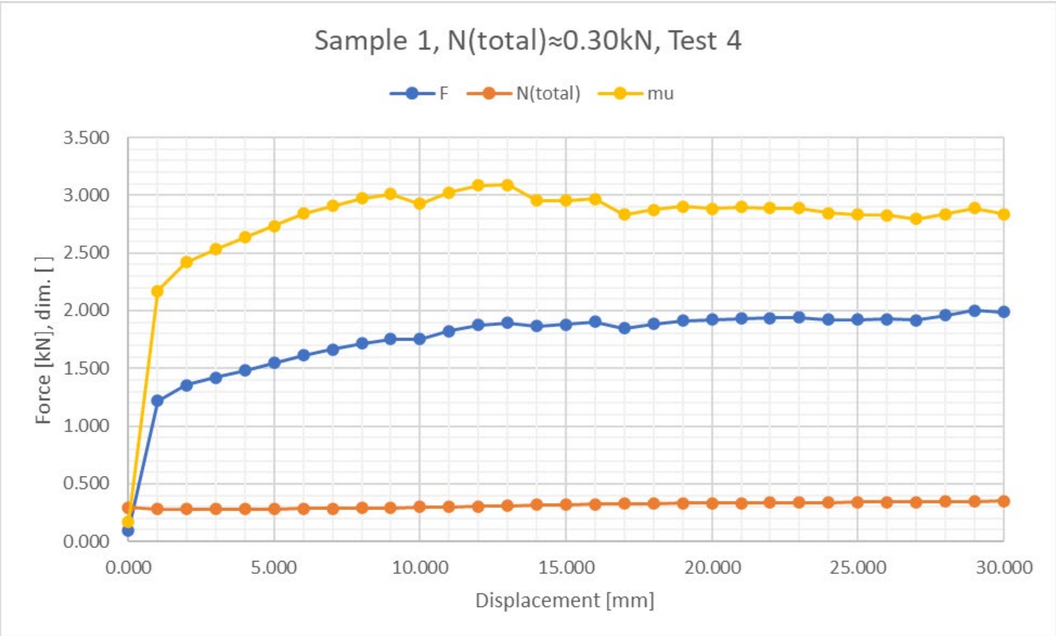


Figure 104: Sample 1, Ntotal=0.30kN, test 4, graph showing variation of F, Ntotal and mu vs displacement

Each table includes also four calculated variables:

- Normal force (N) in [kN] measured at load cell 1, calculated using equation 13
- Normal force (N) in [kN] measured at load cell 2, calculated using equation 14
- Total normal force (Ntotal) in [kN] which is the sum of normal forces measured at load cells 1 and 2
- Friction coefficient (mu) which has no dimensions and is calculated using equation 12:

mu = 0.5*F/Ntotal

Each data table is followed by the figure that shows on one graph how variables such as load from the press (F) [kN], total normal force (Ntotal) [kN] and friction coefficient (mu) [dimentionless] are changing with the displacement of the sliding plate.

For the following samples 2 – 6 only figures with graphs showing variation of F, Ntotal and mu vs displacement will be illustrated. Tables that show the data acquired from rectangular pushout tests on these samples can be reviewed in Appendix B.

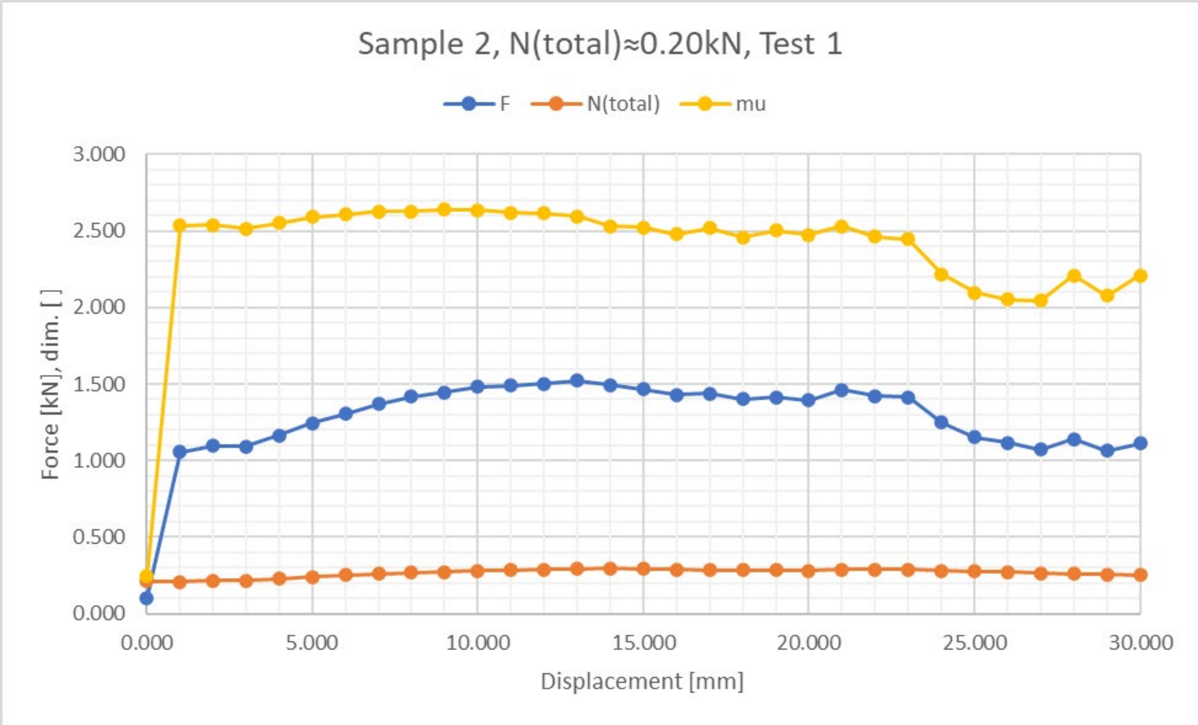


Figure 105: Sample 2, Ntotal=0.20kN, test 1, graph showing variation of F, Ntotal and mu vs displacement

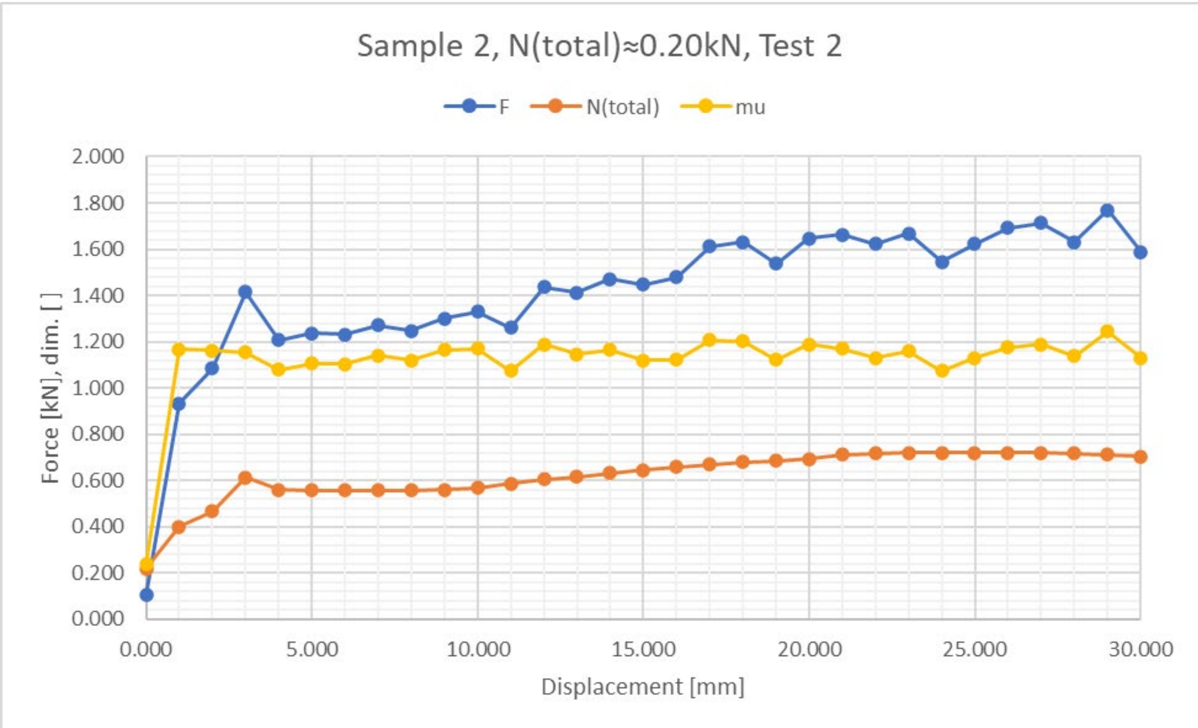


Figure 106: Sample 2, Ntotal=0.20kN, test 2, graph showing variation of F, Ntotal and mu vs displacement

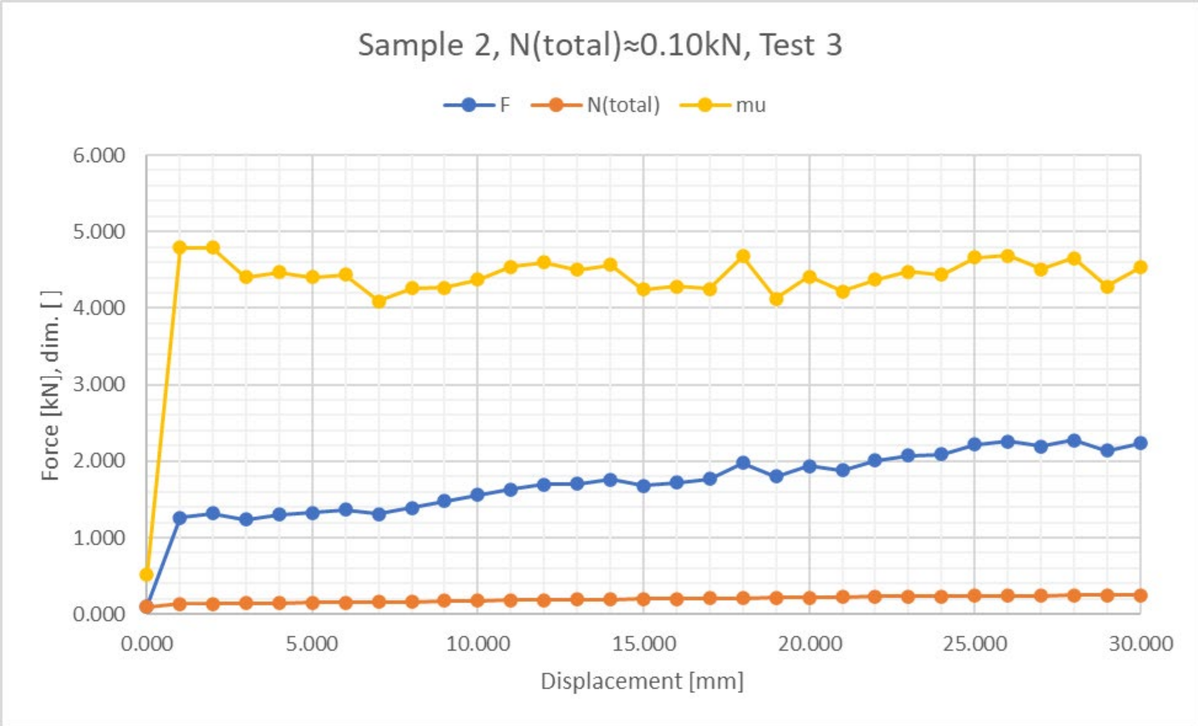


Figure 107: Sample 2, Ntotal=0.20kN, test 1, graph showing variation of F, Ntotal and mu vs displacement

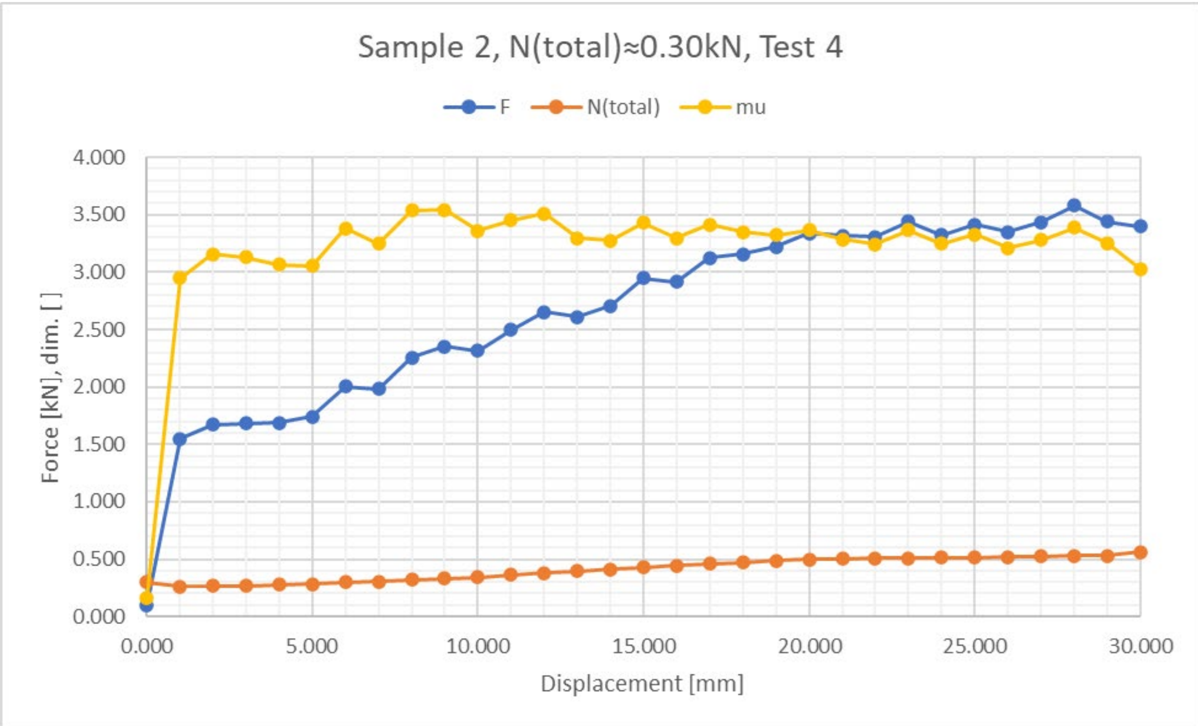


Figure 108: Sample 2, Ntotal=0.20kN, test 2, graph showing variation of F, Ntotal and mu vs displacement

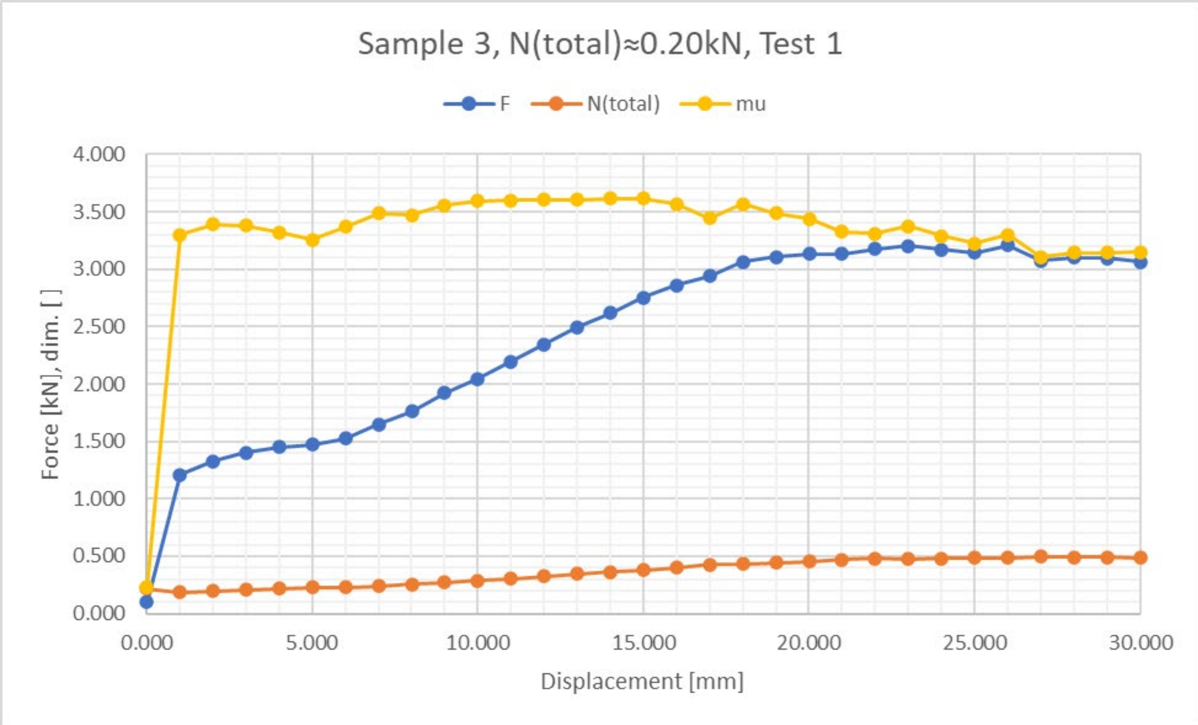


Figure 109: Sample 3, Ntotal=0.20kN, test 1, graph showing variation of F, Ntotal and mu vs displacement

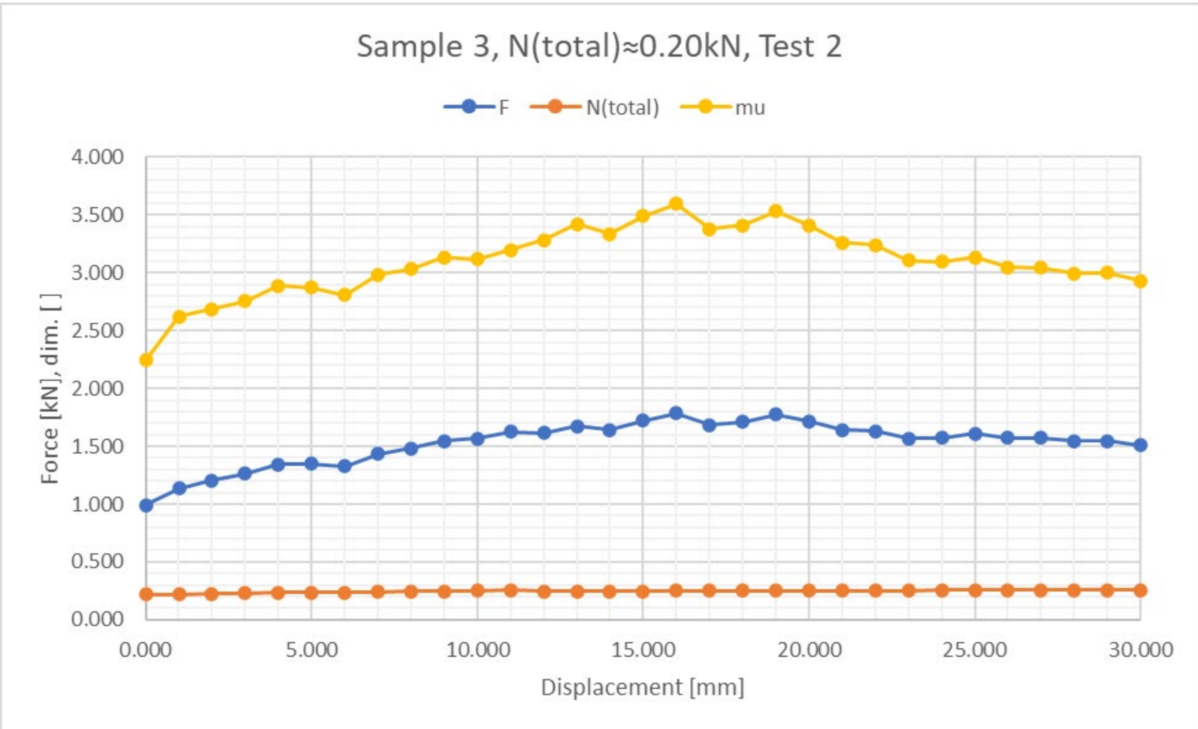


Figure 110: Sample 3, Ntotal=0.20kN, test 2, graph showing variation of F, Ntotal and mu vs displacement

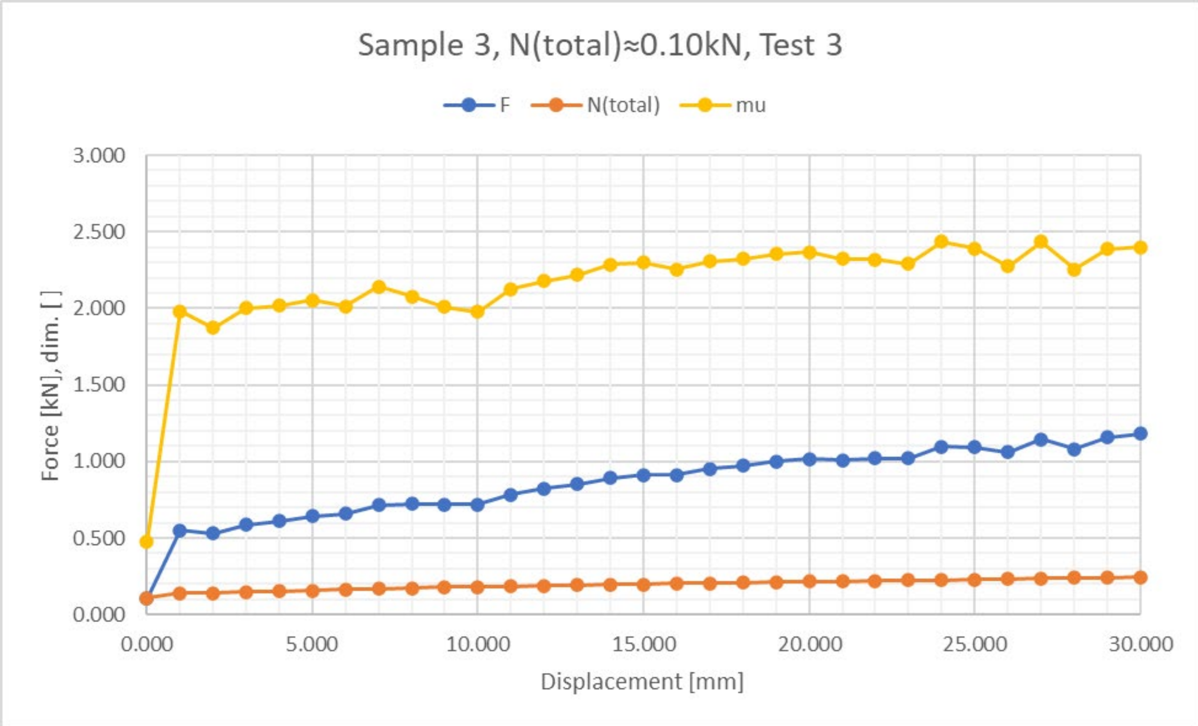


Figure 111: Sample 3, Ntotal=0.10kN, test 3, graph showing variation of F, Ntotal and mu vs displacement

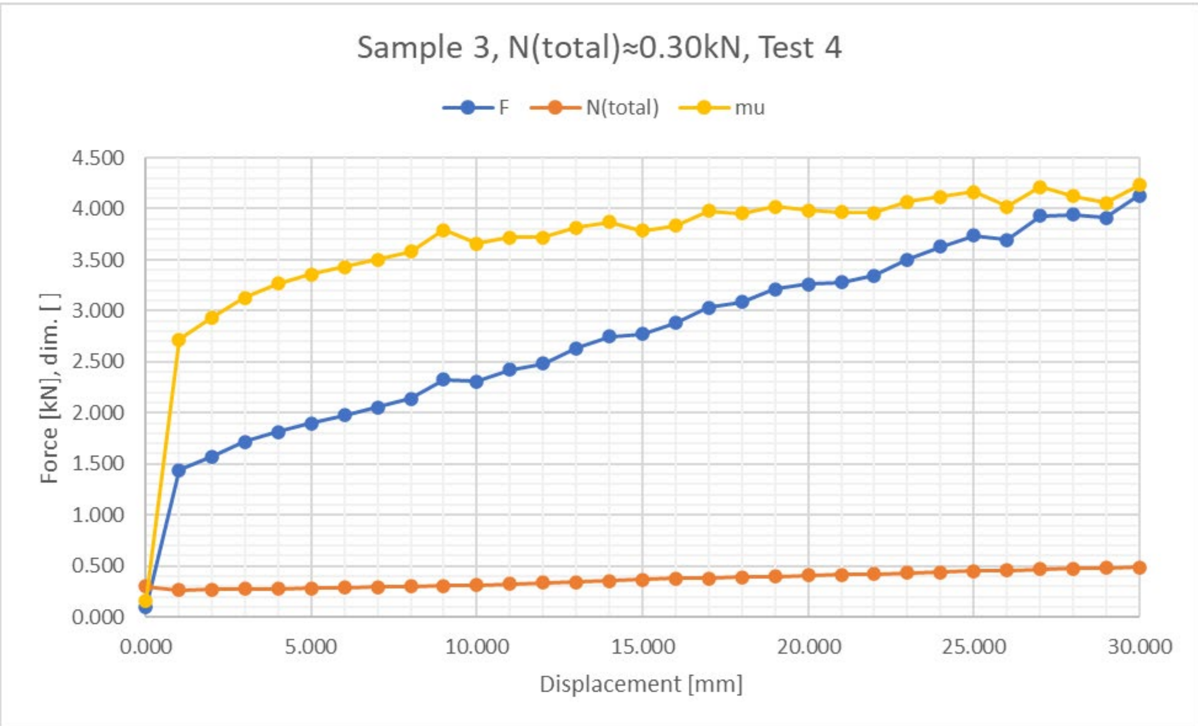


Figure 112: Sample 3, Ntotal=0.30kN, test 4, graph showing variation of F, Ntotal and mu vs displacement

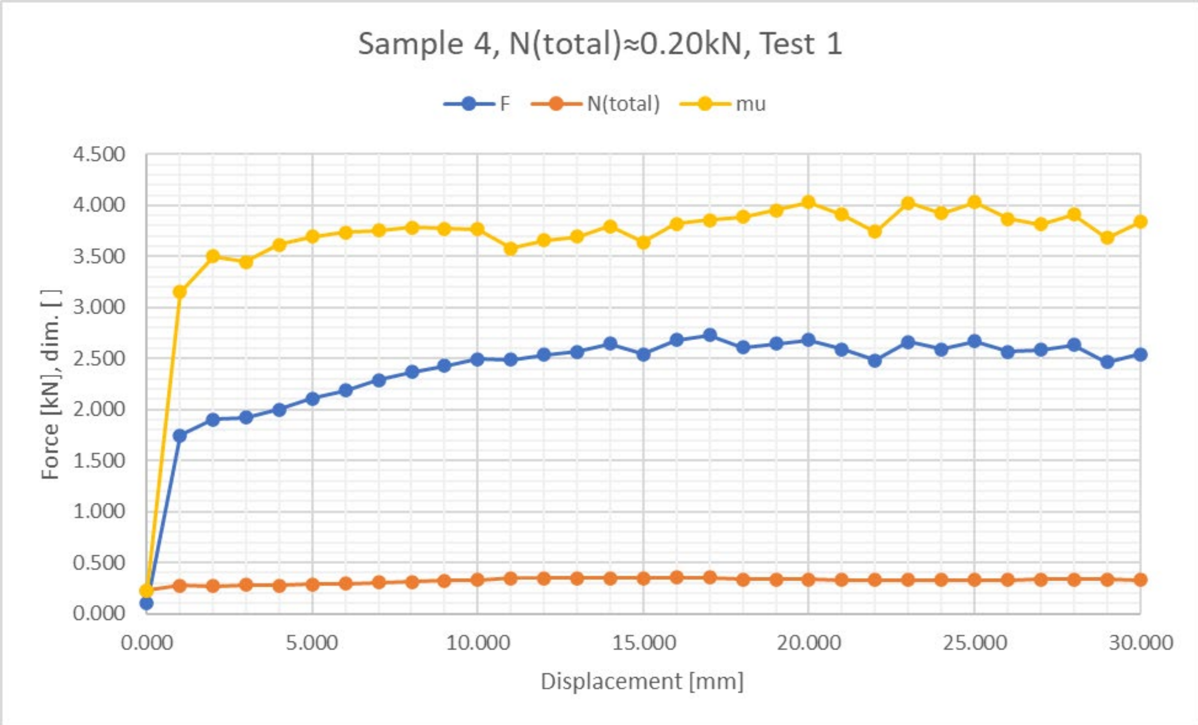


Figure 113: Sample 4, Ntotal=0.20kN, test 1, graph showing variation of F, Ntotal and mu vs displacement

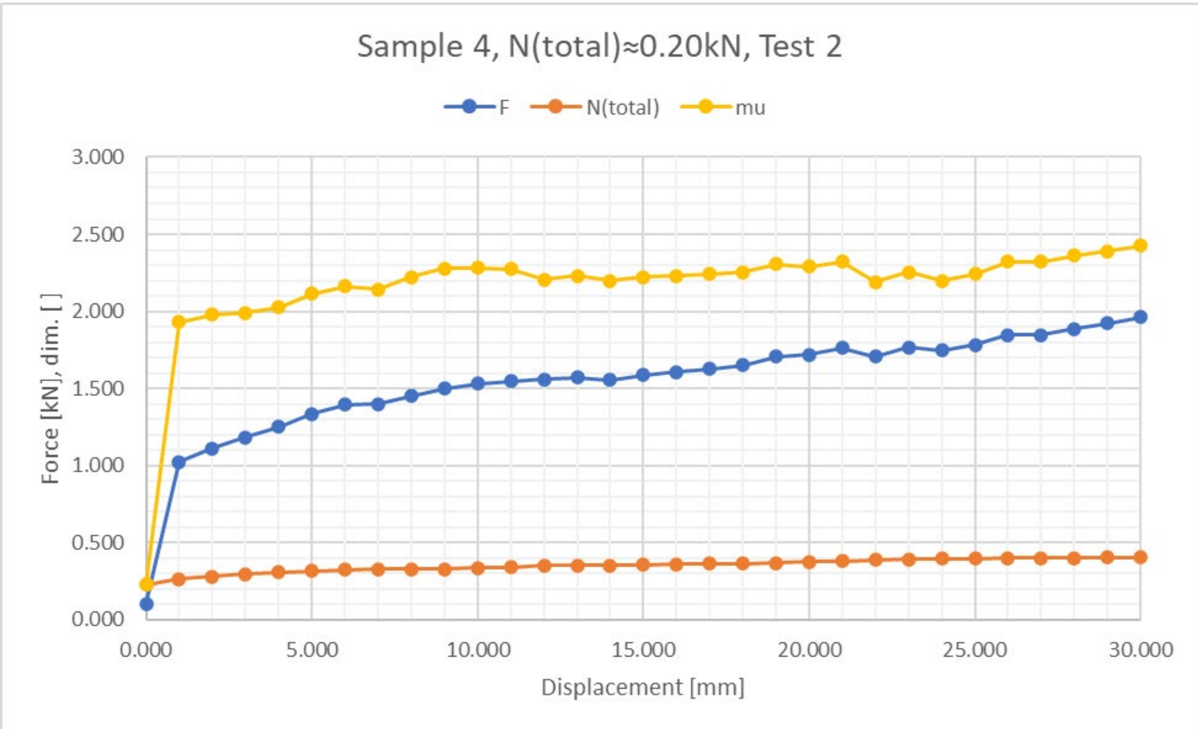


Figure 114: Sample 4, Ntotal=0.20kN, test 2, graph showing variation of F, Ntotal and mu vs displacement

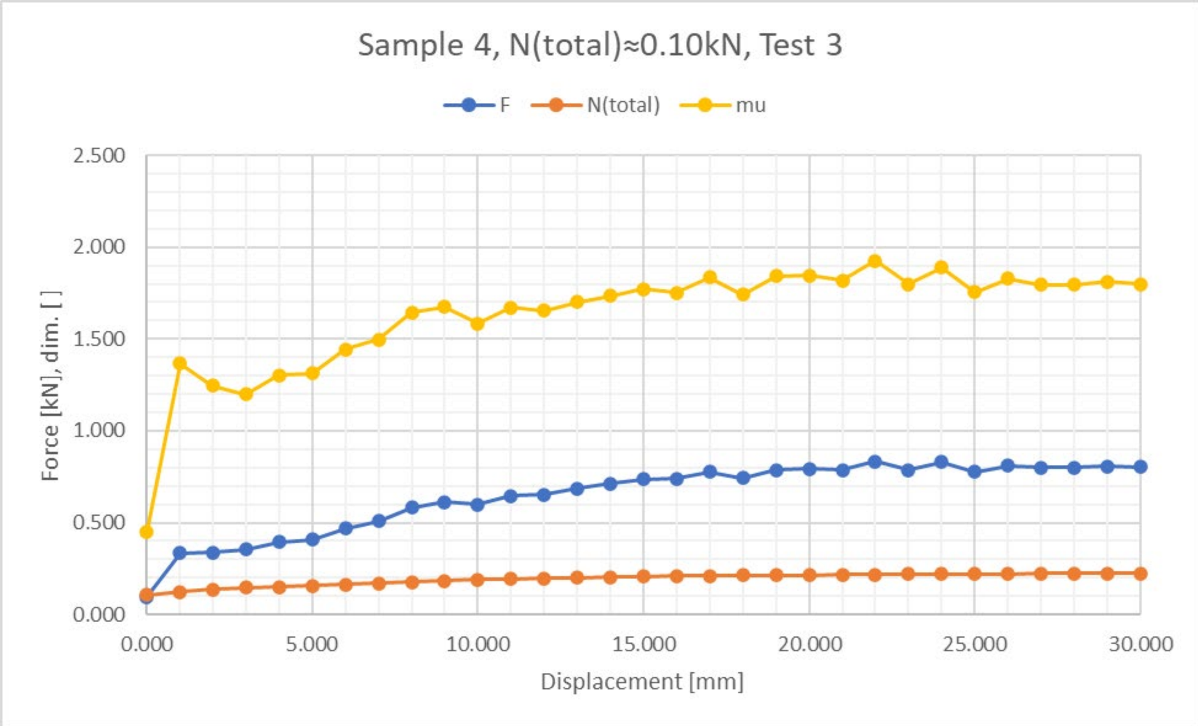


Figure 115: Sample 4, Ntotal=0.10kN, test 3, graph showing variation of F, Ntotal and mu vs displacement

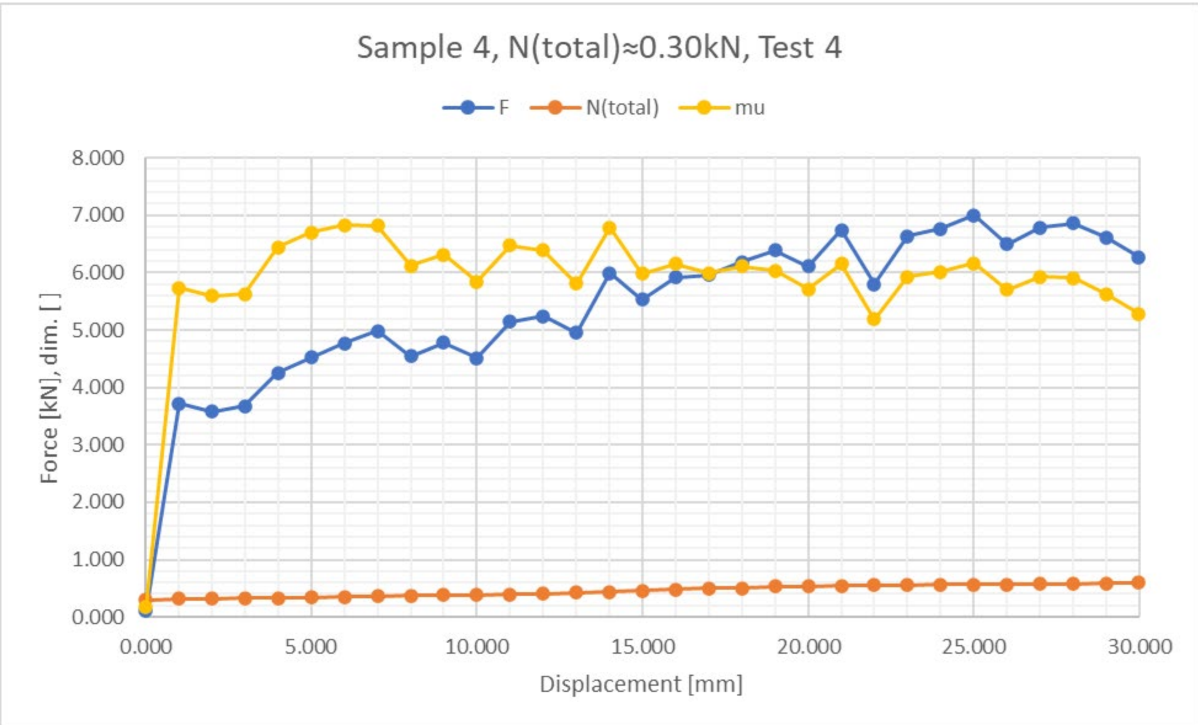


Figure 116: Sample 4, Ntotal=0.30kN, test 4, graph showing variation of F, Ntotal and mu vs displacement

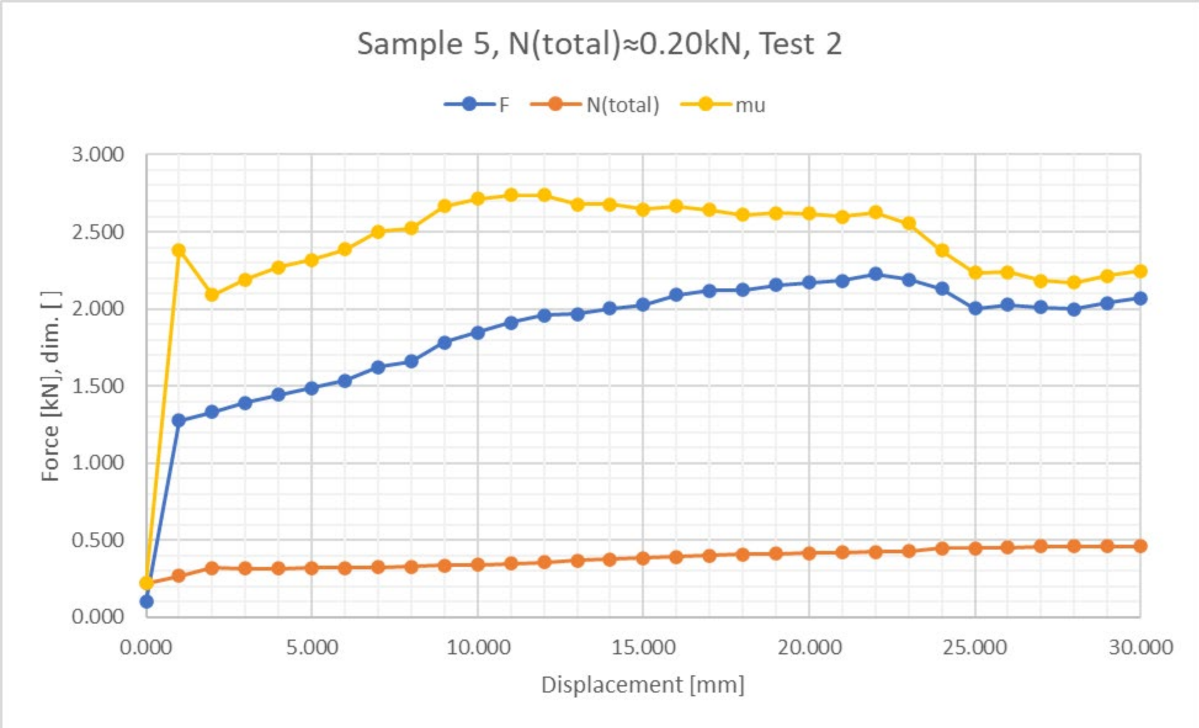


Figure 117: Sample 5, Ntotal=0.20kN, test 2, graph showing variation of F, Ntotal and mu vs displacement

Figure for test 1 for sample 5 is missing because the test has failed making the collected data for it meaningless for this research.

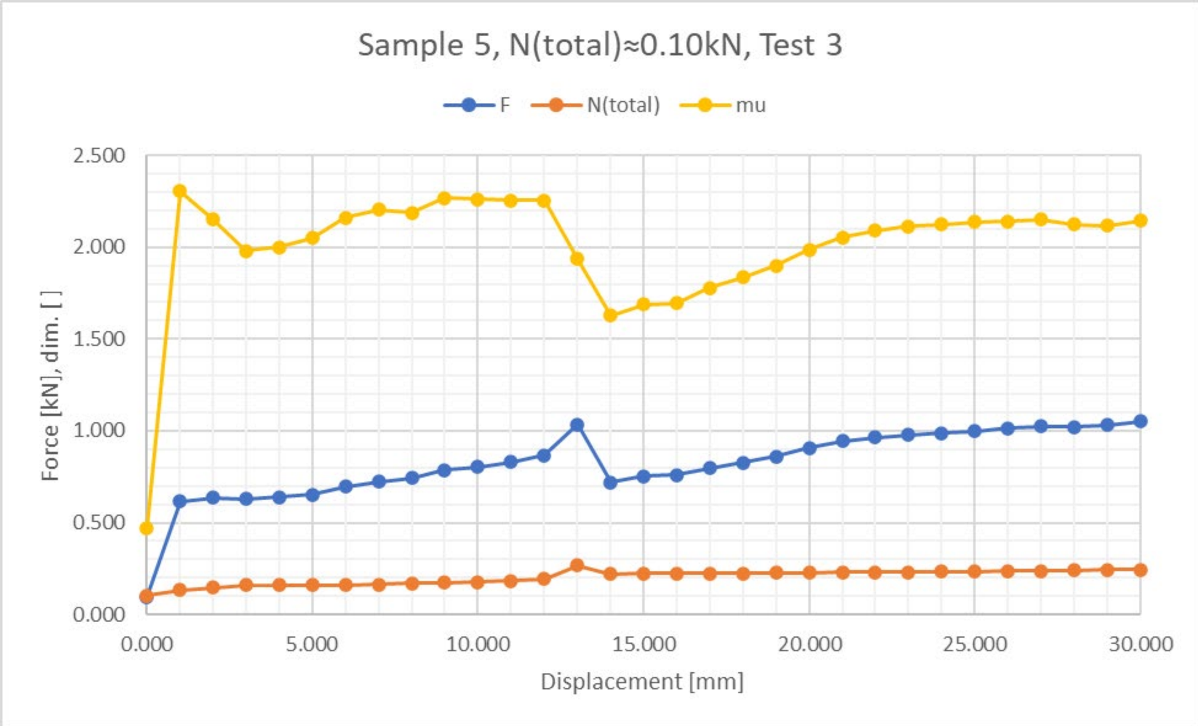


Figure 118: Sample 5, Ntotal=0.10kN, test 3, graph showing variation of F, Ntotal and mu vs displacement

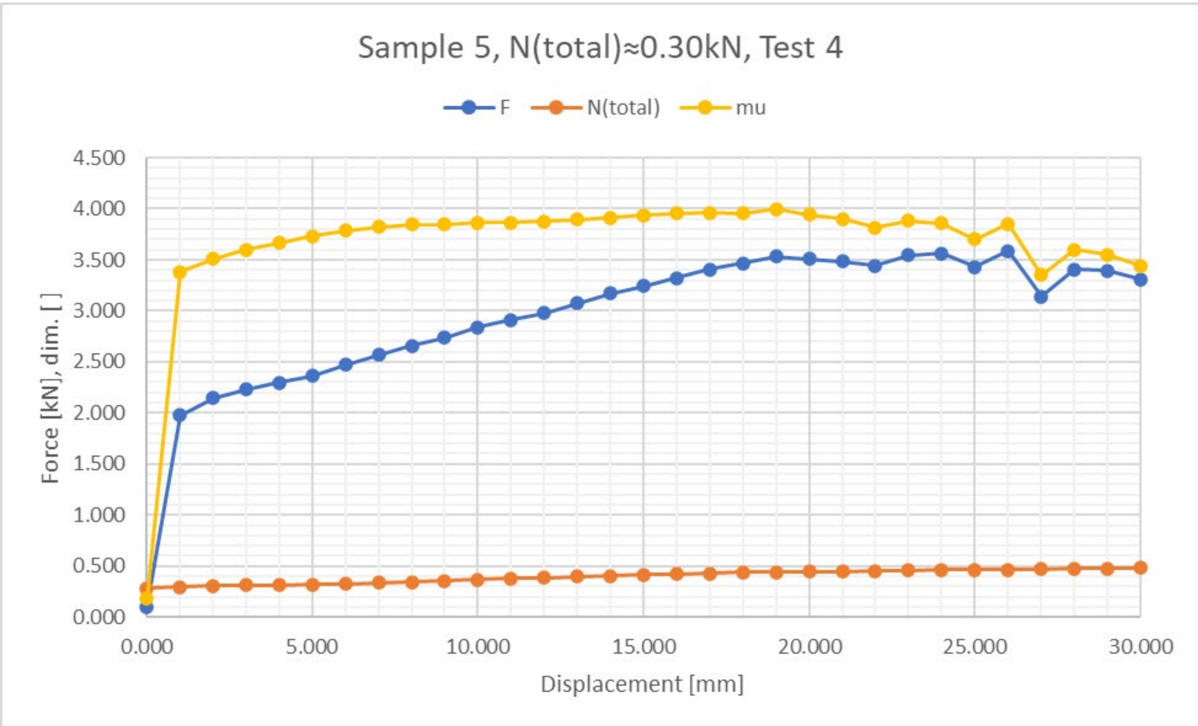


Figure 119: Sample 5, Ntotal=0.30kN, test 4, graph showing variation of F, Ntotal and mu vs displacement

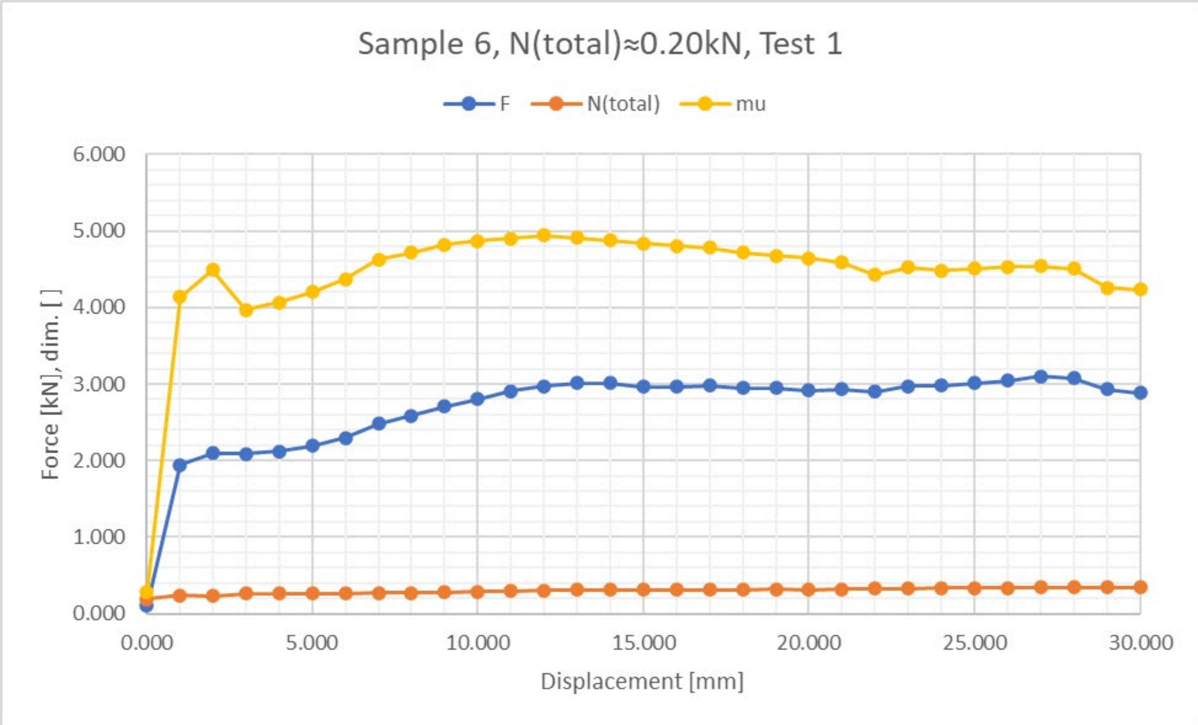


Figure 120: Sample 6, Ntotal=0.20kN, test 1, graph showing variation of F, Ntotal and mu vs displacement

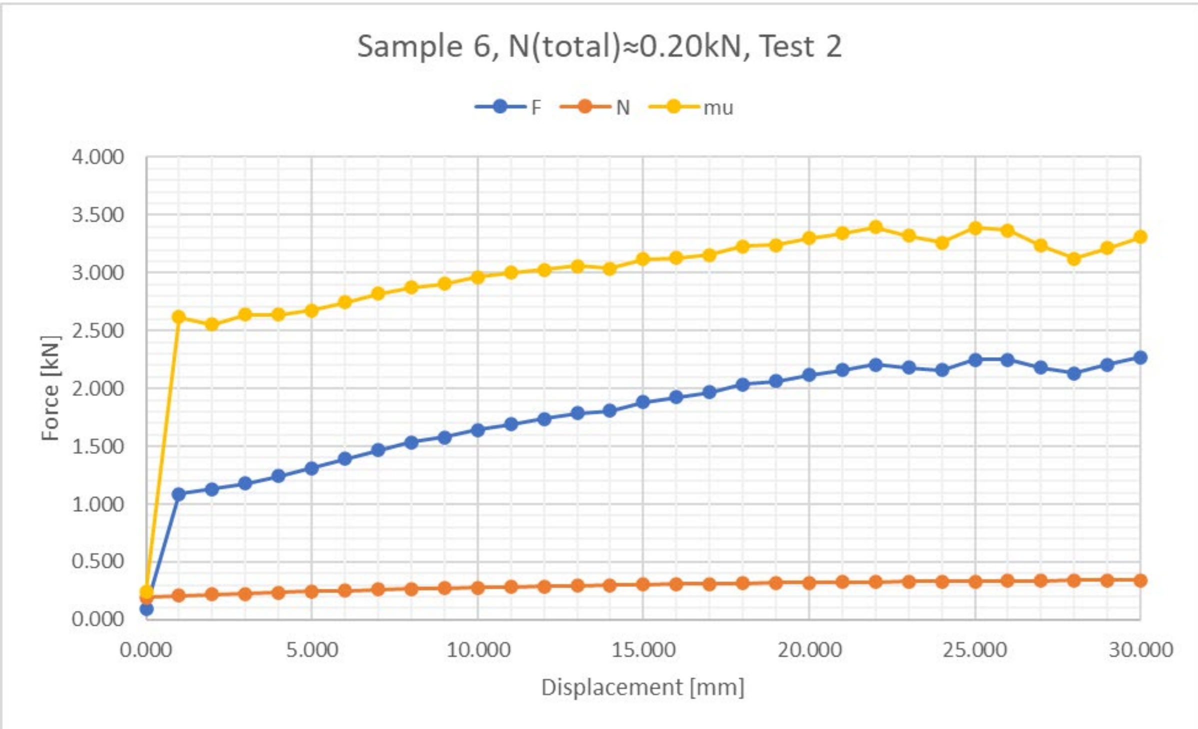


Figure 121: Sample 6, Ntotal=0.20kN, test 2, graph showing variation of F, Ntotal and mu vs displacement

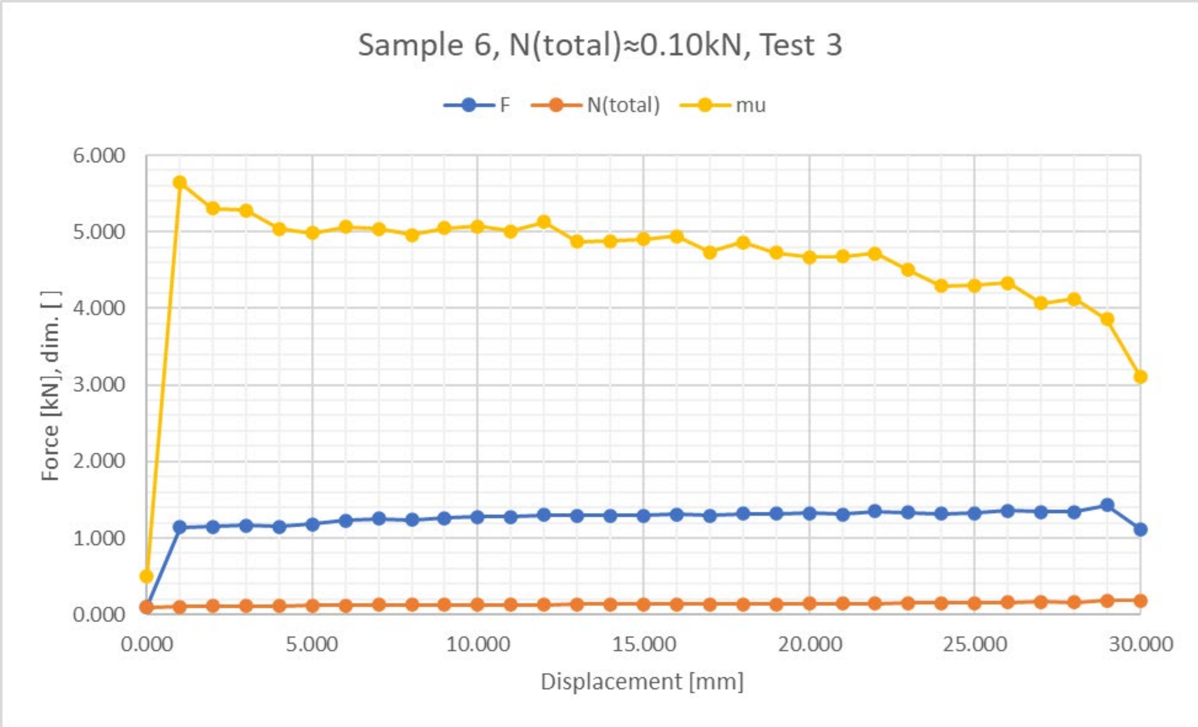


Figure 122: Sample 6, Ntotal=0.10kN, test 3, graph showing variation of F, Ntotal and mu vs displacement

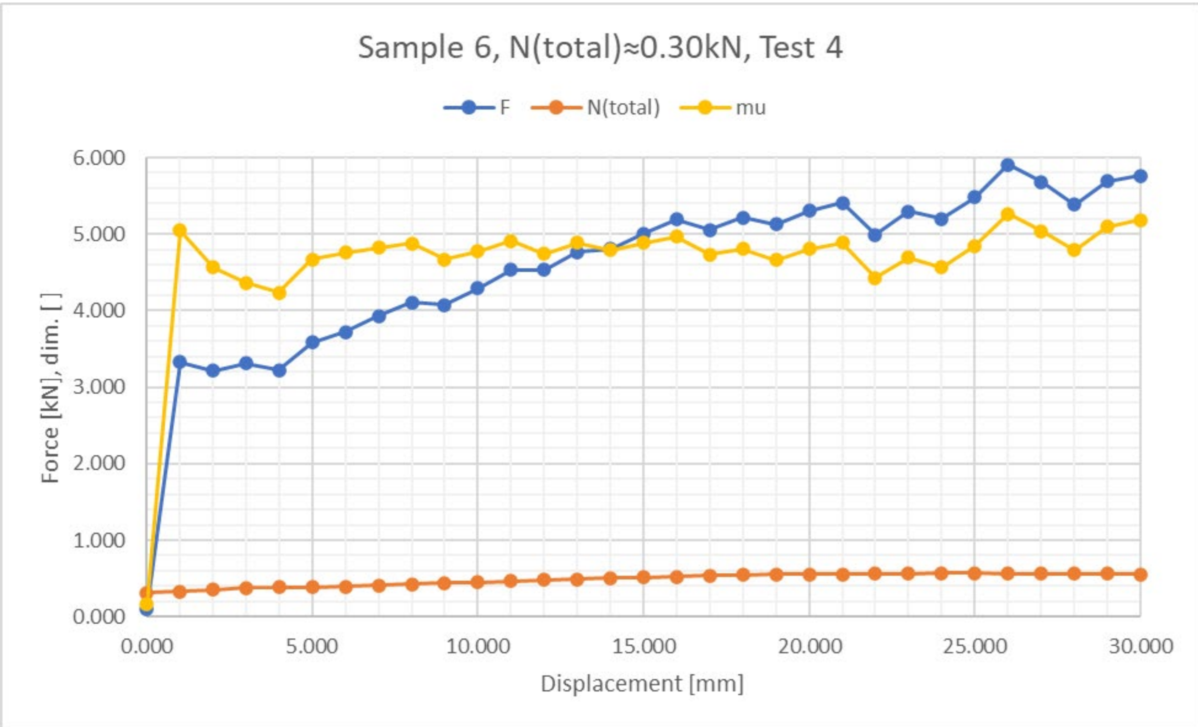


Figure 123: Sample 6, Ntotal=0.30kN, test 4, graph showing variation of F, Ntotal and mu vs displacement

Following data tables 12 – 17 represent mean values and standard deviations of kinetic mu calculated in Excel for each one of four tests. Two sets of values are given for each test: one for all data points of mu in the test and another for all data points except the first one that is at 0.00mm displacement. Table 18 provides the summary and represents calculated mean and STD of kinetic mu for each one of four tests combined from samples 1 - 6

Table 12: Calculated mean and STD of kinetic mu for each one of four tests for sample 1

Sample 1					
Test No	N(init) [kN]	kinetic mu			
		All data		Data except 1st point	
		Mean	STD	Mean	STD
1	0.20	2.730	0.638	2.814	0.446
2	0.20	1.920	0.343	1.977	0.133
3	0.10	1.988	0.309	2.037	0.138
4	0.30	2.755	0.515	2.842	0.190

Table 13: Calculated mean and STD of kinetic mu for each one of four tests for sample 2

Sample 2					
Test No	N(init) [kN]	kinetic mu			
		All data		Data except 1st point	
		Mean	STD	Mean	STD
1	0.20	2.380	0.439	2.451	0.192
2	0.20	1.119	0.168	1.148	0.040
3	0.10	4.318	0.729	4.444	0.185
4	0.30	3.191	0.580	3.292	0.147

Table 14: Calculated mean and STD of kinetic mu for each one of four tests for sample 3

Sample 3					
Test No	N(init) [kN]	kinetic mu			
		All data		Data except 1st point	
		Mean	STD	Mean	STD
1	0.20	3.299	0.591	3.401	0.160
2	0.20	3.099	0.296	3.128	0.254
3	0.10	2.156	0.351	2.212	0.162
4	0.30	3.650	0.748	3.766	0.381

Table 15: Calculated mean and STD of kinetic mu for each one of four tests for sample 4

Sample 4					
Test No	N(init) [kN]	kinetic mu			
		All data		Data except 1st point	
		Mean	STD	Mean	STD
1	0.20	3.649	0.662	3.763	0.186
2	0.20	2.156	0.376	2.221	0.118
3	0.10	1.629	0.297	1.668	0.205
4	0.30	5.855	1.133	6.044	0.418

Table 16: Calculated mean and STD of kinetic mu for each one of four tests for sample 5

Sample 5					
Test No	N(init) [kN]	kinetic mu			
		All data		Data except 1st point	
		Mean	STD	Mean	STD
1	0.20	N/A	N/A	N/A	N/A
2	0.20	2.399	0.452	2.471	0.208
3	0.10	2.005	0.337	2.057	0.182
4	0.30	3.660	0.670	3.776	0.182

Table 17: Calculated mean and STD of kinetic mu for each one of four tests for sample 6

Sample 6					
Test No	N(init) [kN]	kinetic mu			
		All data		Data except 1st point	
		Mean	STD	Mean	STD
1	0.20	4.426	0.814	4.565	0.268
2	0.20	2.965	0.566	3.056	0.260
3	0.10	4.602	0.906	4.738	0.501
4	0.30	4.643	0.861	4.793	0.225

Table 18: Calculated mean and STD of kinetic mu for each one of four tests combined from samples 1 - 6

All Samples 1 - 6					
Test No	N(init) [kN]	kinetic mu			
		All data		Data except 1st point	
		Mean	STD	Mean	STD
1	0.20	3.297	0.957	3.399	0.788
2	0.20	2.276	0.768	2.333	0.699
3	0.10	2.783	1.316	2.859	1.268
4	0.30	3.959	1.282	4.085	1.095
All tests		3.069	1.277	3.159	1.195

As seen from the graphs on figures 101 – 123 where the variation of kinetic mu vs displacement is shown, the first value of mu at 0.00mm displacement greatly differs in value from other data for mu. This is also shown on the tables 12 – 17 where the mean values of kinetic mu are calculated first including all points and then including all except for the first point at 0.00mm displacement.

Table 19 represents mean values and standard deviations of kinetic mu, calculated for each test for each one of six samples (third column from the left). Column four and five (from the left) represent mean values of kinetic mu and their standard deviations combined for each sample. Final two columns represent mean value and standard deviation of kinetic mu combined from all samples. Same mean value and STD of kinetic mu calculated for all samples together is also found in table 18 before.

Table 19: Mean values and STD of kinetic mu combined for each test, each sample and all samples together

kinetic mu						
Sample	Test No	mu	mean	std	mean	std
1	1	2.730	2.348	0.611	3.069	1.277
	2	1.920				
	3	1.988				
	4	2.755				
2	1	2.380	2.752	1.280		
	2	1.119				
	3	4.318				
	4	3.191				
3	1	3.299	3.051	0.762		
	2	3.099				
	3	2.156				
	4	3.650				
4	1	3.649	3.322	1.785		
	2	2.156				
	3	1.629				
	4	5.855				
5	1	-	2.688	0.868		
	2	2.399				
	3	2.005				
	4	3.660				
6	1	4.426	4.159	1.052		
	2	2.965				
	3	4.602				
	4	4.643				

4.4 Results from conventional friction experiments on an inclined plane

Following data tables 20 - 21 represent the data collected from conventional friction experiments. Tables 20 and 21 represent inclined and vertical length measurements [cm] gathered during experiments. Those are used to calculate angles 'α' and 'β'. Final columns in table 20 and table 21 contains values of static friction coefficient (mu static) and kinetic friction coefficient (mu kinetic) respectively.

Table 20: Data from conventional experiment showing mu static calculated for each test

Static friction coefficient (mu static)						
Sample	Test	Length inclined [cm]	Length vertical [cm]	Angle ß [deg]	Angle α [deg]	mu
1	1	60.8	14.8	14.09	75.91	0.25
	2	59.2	16.4	16.08	73.92	0.29
	3	59.2	16.3	15.98	74.02	0.29
	1	59.8	15.9	15.42	74.58	0.28
	2	59.8	15.8	15.32	74.68	0.27
	3	60.4	14.8	14.18	75.82	0.25
2	1	58.7	17.0	16.83	73.17	0.30
	2	58.5	17.1	17.00	73.00	0.31
	3	59.2	16.4	16.08	73.92	0.29
	1	55.7	21.1	22.26	67.74	0.41
	2	58.5	17.3	17.20	72.80	0.31
	3	57.3	18.6	18.94	71.06	0.34
3	1	59.5	16.2	15.80	74.20	0.28
	2	60.2	15.5	14.92	75.08	0.27
	3	59.0	16.7	16.44	73.56	0.30
	1	58.8	16.9	16.70	73.30	0.30
	2	59.1	16.6	16.31	73.69	0.29
	3	59.6	16.0	15.57	74.43	0.28
4	1	58.5	17.3	17.20	72.80	0.31
	2	58.8	16.9	16.70	73.30	0.30
	3	59.0	16.7	16.44	73.56	0.30
	1	59.2	16.6	16.28	73.72	0.29
	2	60.3	15.4	14.80	75.20	0.26
	3	59.9	15.8	15.29	74.71	0.27
5	1	58.4	17.4	17.33	72.67	0.31
	2	58.7	17.0	16.83	73.17	0.30
	3	58.8	16.9	16.70	73.30	0.30
	1	57.8	18.1	18.25	71.75	0.33
	2	58.5	17.3	17.20	72.80	0.31
	3	59.5	16.3	15.90	74.10	0.28
6	1	58.1	17.7	17.74	72.26	0.32
	2	59.0	16.8	16.54	73.46	0.30
	3	57.5	18.3	18.56	71.44	0.34
	1	57.9	18.0	18.11	71.89	0.33
	2	58.9	16.7	16.47	73.53	0.30
	3	57.9	18.0	18.11	71.89	0.33

Table 21: Data from conventional experiment showing mu kinetic calculated for each test

Kinetic friction coefficient (mu kinetic)						
Sample	**Test**	**Length inclined [cm]**	**Length vertical [cm]**	**Angle ß [deg]**	**Angle α [deg]**	**mu**
1	1	59.7	16.1	15.65	74.35	0.28
	2	59.0	16.6	16.34	73.66	0.29
	3	59.2	16.5	16.18	73.82	0.29
	1	61.1	14.8	14.02	75.98	0.25
	2	60.6	15.1	14.43	75.57	0.26
	3	60.3	15.4	14.80	75.20	0.26
2	1	60.8	15.0	14.28	75.72	0.25
	2	60.1	15.6	15.04	74.96	0.27
	3	60.2	15.5	14.92	75.08	0.27
	1	59.6	16.1	15.67	74.33	0.28
	2	58.9	16.7	16.47	73.53	0.30
	3	58.2	17.6	17.60	72.40	0.32
3	1	59.2	16.9	16.59	73.41	0.30
	2	59.8	15.9	15.42	74.58	0.28
	3	59.7	16.0	15.55	74.45	0.28
	1	58.6	17.2	17.07	72.93	0.31
	2	58.2	17.6	17.60	72.40	0.32
	3	58.5	17.1	17.00	73.00	0.31
4	1	60.2	15.6	15.02	74.98	0.27
	2	60.0	15.9	15.37	74.63	0.27
	3	60.3	15.5	14.89	75.11	0.27
	1	59.3	16.4	16.05	73.95	0.29
	2	59.2	16.6	16.28	73.72	0.29
	3	59.4	16.3	15.93	74.07	0.29
5	1	60.6	15.2	14.53	75.47	0.26
	2	61.0	14.9	14.14	75.86	0.25
	3	60.9	14.9	14.16	75.84	0.25
	1	60.5	15.3	14.65	75.35	0.26
	2	59.7	15.9	15.45	74.55	0.28
	3	59.5	16.2	15.80	74.20	0.28
6	1	58.5	17.2	17.10	72.90	0.31
	2	59.3	16.4	16.05	73.95	0.29
	3	58.9	16.8	16.57	73.43	0.30
	1	59.0	16.7	16.44	73.56	0.30
	2	59.2	16.5	16.18	73.82	0.29
	3	59.0	16.6	16.34	73.66	0.29

Following tables 22 and 23 represent calculated mean values and standard deviations for static and kinetic friction coefficients respectively. Mean values and their standard deviations are first calculated for each of two blocks in every sample, then for the whole sample, and in the last two columns mean value and standard deviation of mu was calculated for all samples together. Mean values were calculated using 'AVERAGE()' function in Excel. Standard deviations were calculated using 'STDEV.S()' function in Excel.

Table 22: Processed data from conventional experiment for mu static

Static friction coefficient (mu static)							
Sample	Block	Mean per block	STD per block	Mean per sample	STD per sample	Mean total	STD total
1	1	0.28	0.02	0.27	0.02	0.30	0.03
	2	0.27	0.01				
2	1	0.30	0.01	0.33	0.04		
	2	0.35	0.05				
3	1	0.28	0.01	0.29	0.01		
	2	0.29	0.01				
4	1	0.30	0.01	0.29	0.02		
	2	0.28	0.01				
5	1	0.30	0.01	0.31	0.01		
	2	0.31	0.02				
6	1	0.32	0.02	0.32	0.02		
	2	0.32	0.02				

Table 23: Processed data from conventional experiment for mu kinetic

Kinetic friction coefficient (mu kinetic)							
Sample	Block	Mean per block	STD per block	Mean per sample	STD per sample	Mean total	STD total
1	1	0.29	0.01	0.27	0.02	0.28	0.02
	2	0.26	0.01				
2	1	0.26	0.01	0.28	0.02		
	2	0.30	0.02				
3	1	0.28	0.01	0.30	0.02		
	2	0.31	0.01				
4	1	0.27	0.00	0.28	0.01		
	2	0.29	0.00				
5	1	0.25	0.00	0.26	0.01		
	2	0.27	0.01				
6	1	0.30	0.01	0.30	0.01		
	2	0.29	0.00				

4.5 Heatmaps for the data collected from pushout experiments on rectangular assembly

Correlation heatmaps can be used to identify possible links between variables and to show how strong these relationships are. The correlation between several variables is represented by a matrix of values in each heatmap. Positive values indicate a positive relationship, while negative values indicate a negative relationship.

When two variables behave in the same way, of if both are rising or falling at the same time, there is a positive correlation. When one variable is rising while another falls and vice versa, then this is known as a negative correlation.

Correlation can have any value between -1 and 1. The correlation between two variables is stronger the closer the absolute value of correlation is to 1. The color-coding scale makes it simple to quickly spot any links between the variables.

In this section will be presented heatmaps for load, displacement, total normal force and kinetic mu. Figures 125 – 128 are presenting heatmaps for each of the four tests taken for sample 1 respectively. Figures 129 – 132 present heatmaps for test 1 for samples 2,3,4 and 6 respectively.

Heatmaps are a form of visualization that show how strongly two numerical variables are related. They were created in python using the code from the following figure:

```
[7]: import pandas as pd  #Defining necessary libraries
     import seaborn as sns
     import matplotlib.pyplot as plt

[8]: data = pd.read_csv('data1.csv') #reading input file
     data = data.astype(float) #converting data into floats

     fig, ax = plt.subplots(figsize=(10,8)) #creating plot area
     sns.heatmap(data.corr(),cmap='coolwarm',annot=True, fmt=".2f", ax=ax) #defining heatmap
```

Figure 124: Python code for creating a heatmap

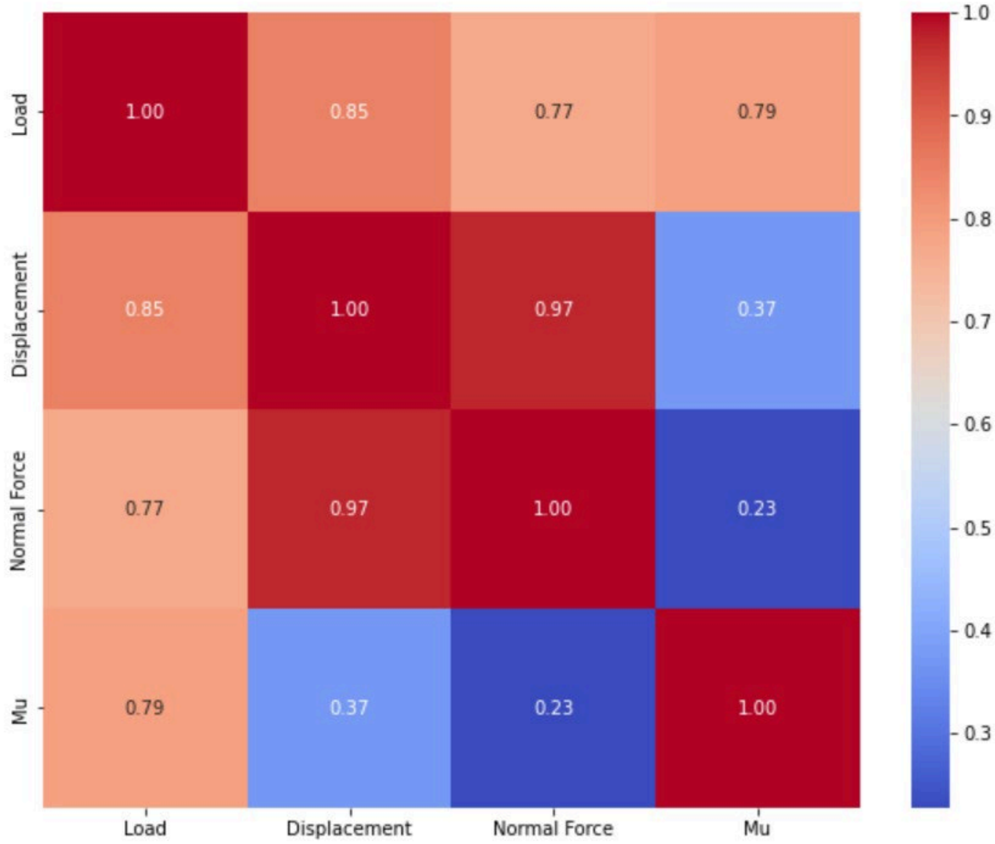


Figure 125: Heatmap for sample 1 test 1

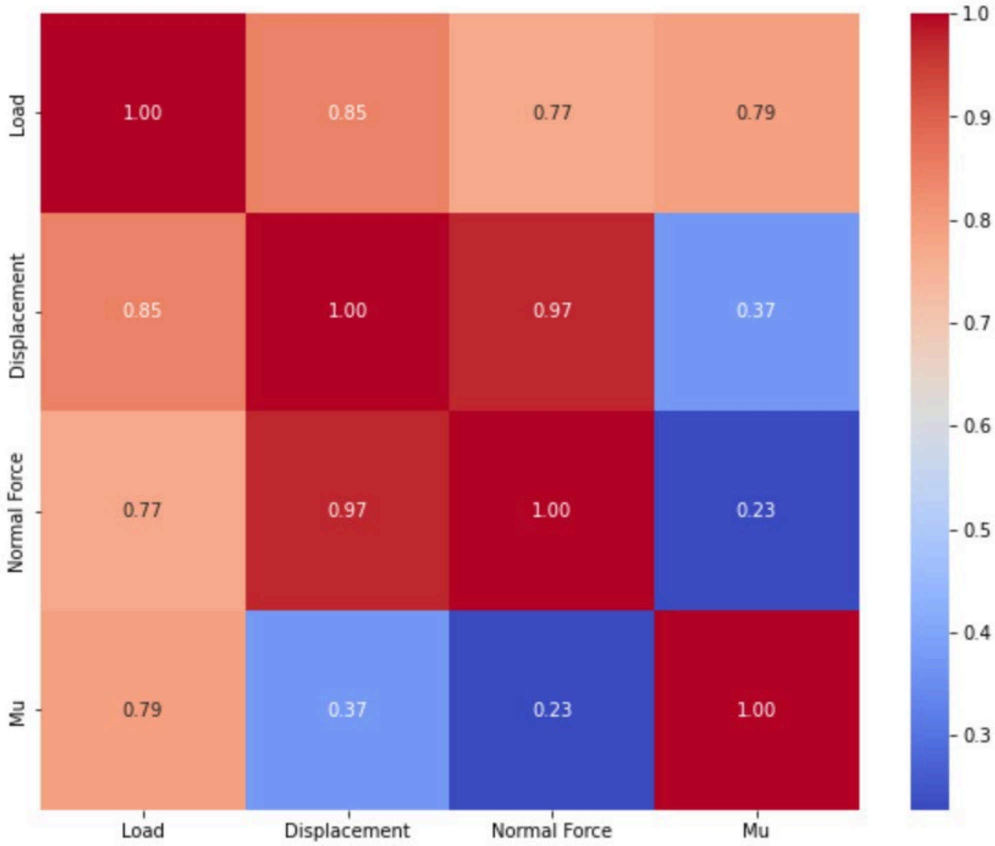


Figure 126: Heatmap for sample 1 test 2

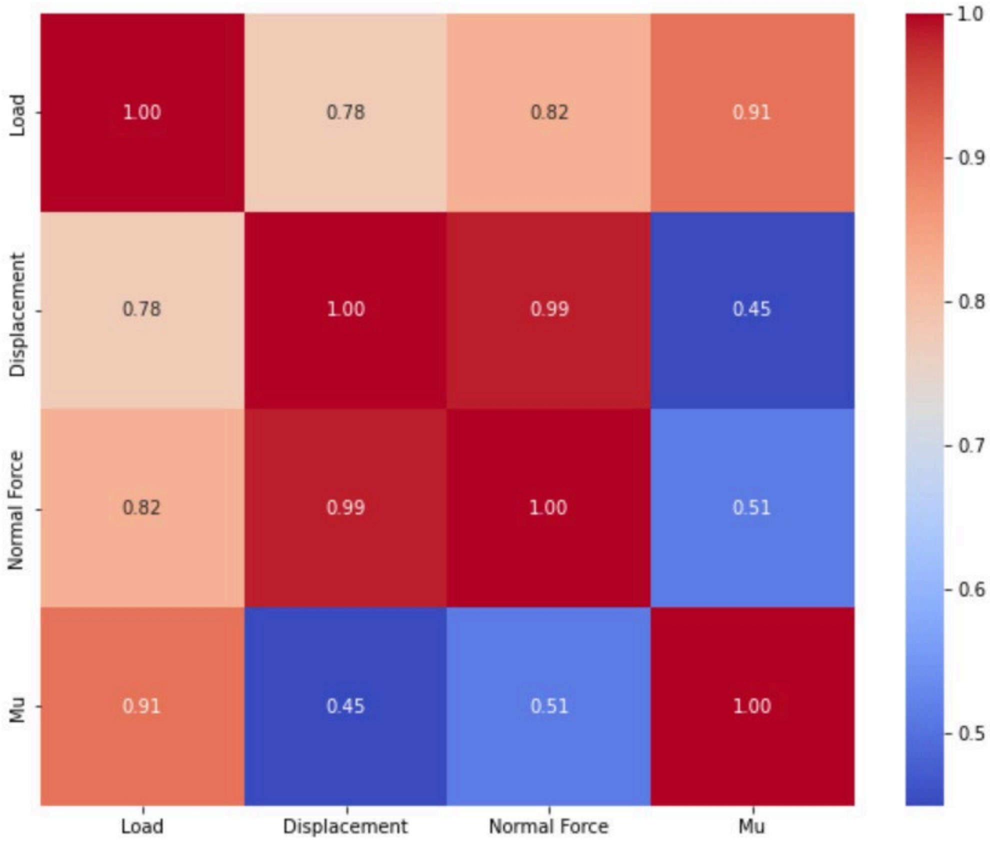


Figure 127: Heatmap for sample 1 test 3

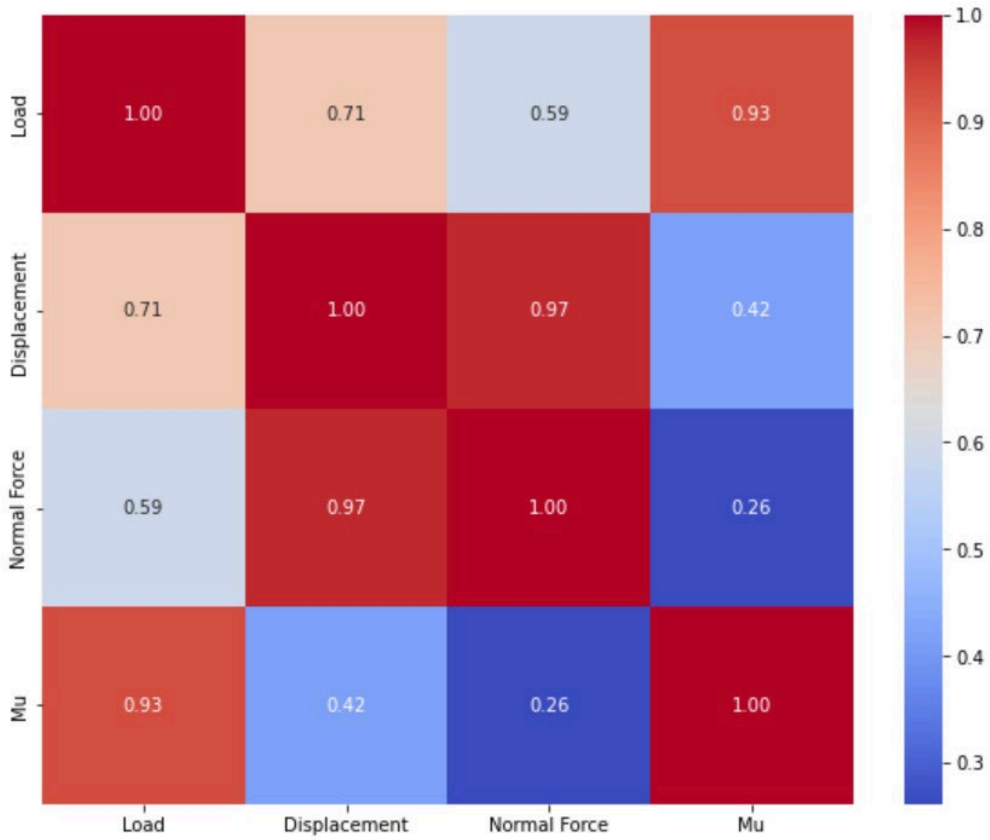


Figure 128: Heatmap for sample 1 test 4

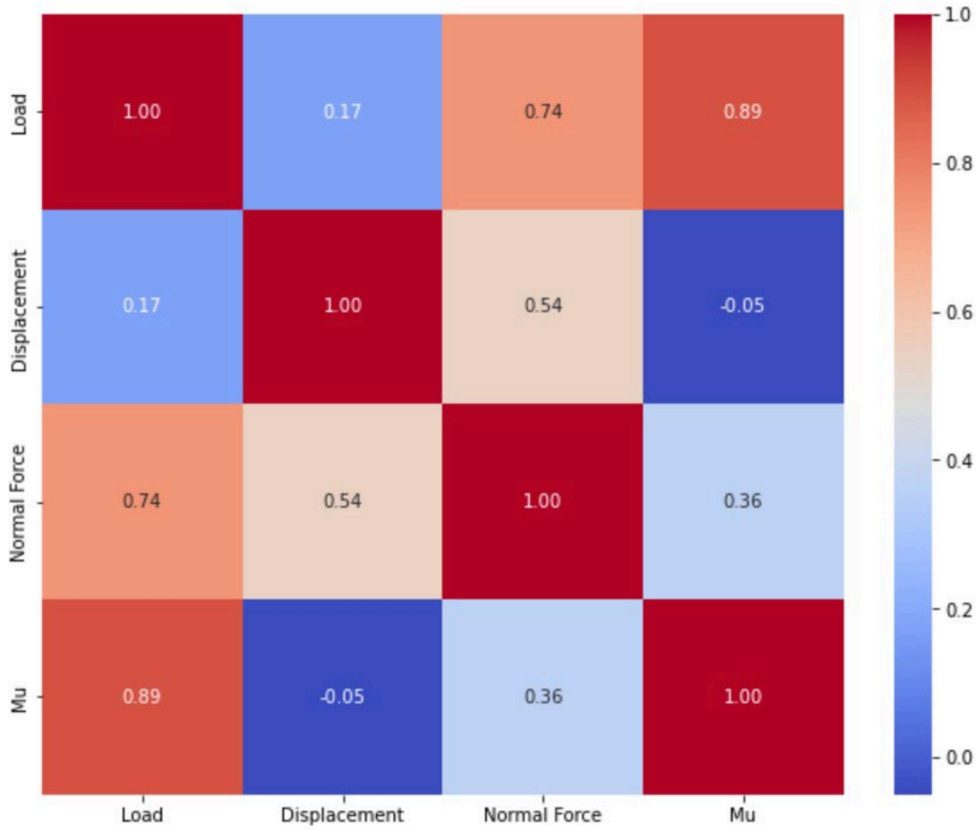


Figure 129: Heatmap for sample 2 test 1

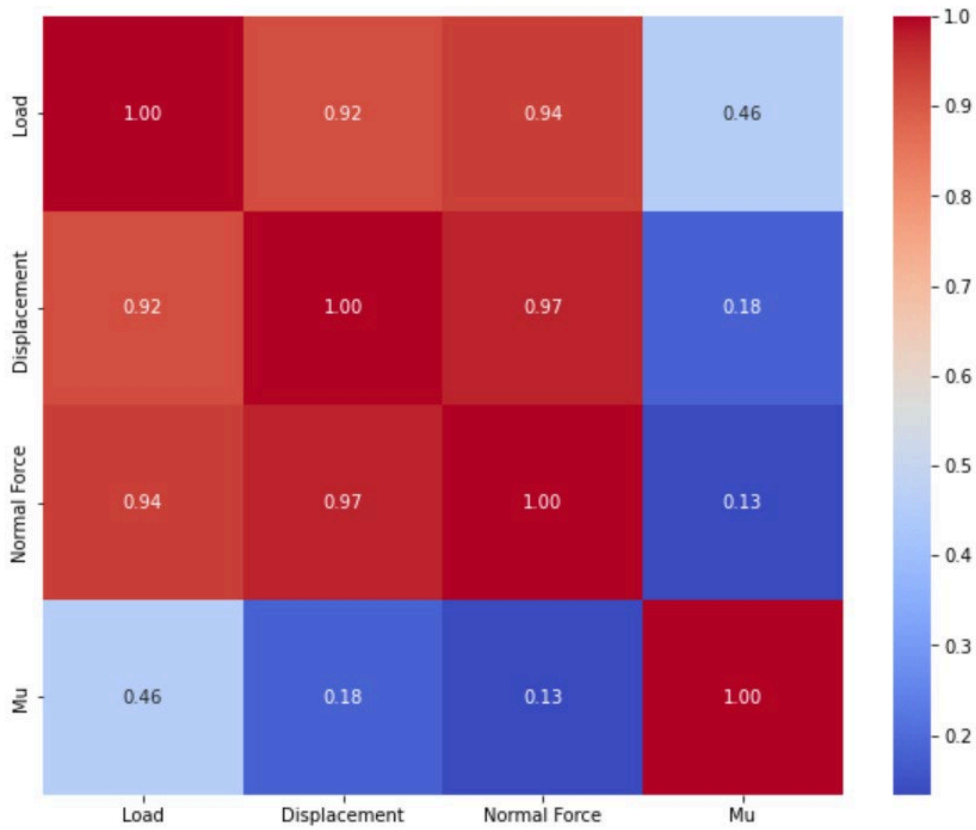


Figure 130: Heatmap for sample 3 test 1

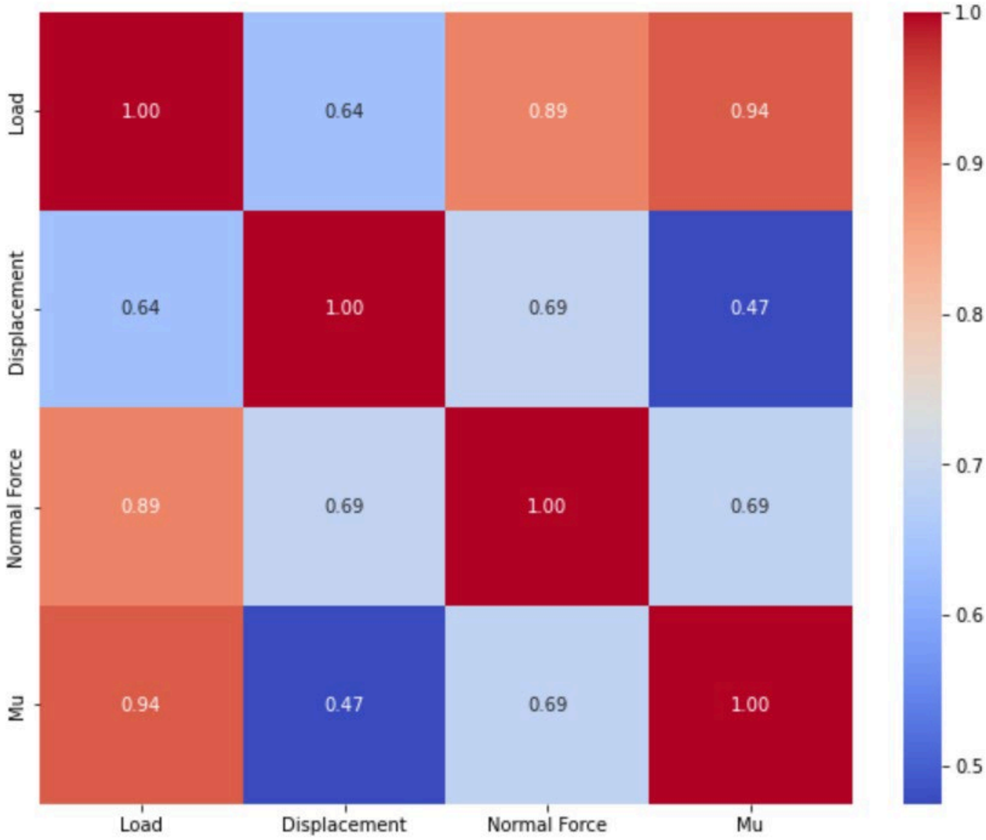


Figure 131: Heatmap for sample 4 test 1

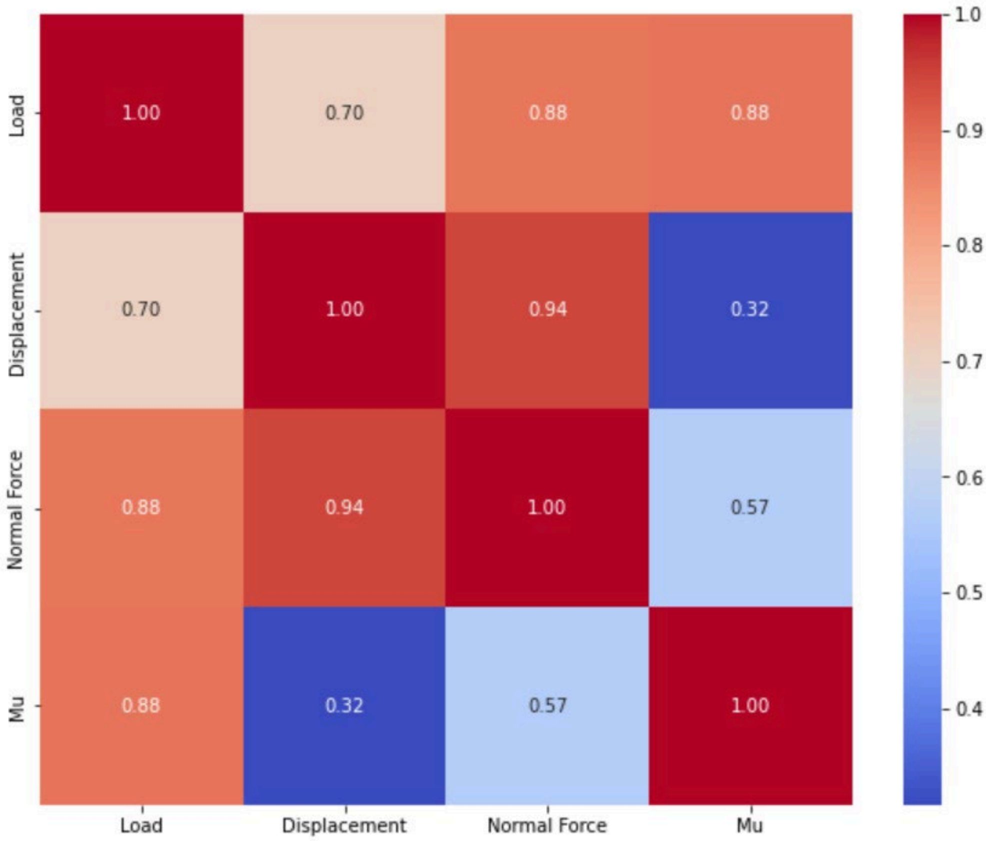


Figure 132: Heatmap for sample 6 test 1

5. Discussion and conclusion

The objective of this research was to study two experimental methods for determining the coefficient of friction between concrete blocks and steel plate. Concrete blocks were molded from API class G cement mixture and steel plate is normal carbon steel. The first method was a well-known conventional method that uses an object sliding on an inclined plane. An angle between a horizontal and inclined plane was then used to find the coefficient of friction. For static and kinetic coefficients of friction experimental procedures differ slightly but the principle stays the same. As the block of sample is sliding on the inclined plane it does not experience any confinement, it has only one surface that is in contact with an inclined plane.

The second method has been developed as a part of this research. It is called method of determining coefficient of friction using pushout test on a confined plate. In this method, kinetic coefficient of friction only was determined from the ratio of vertical load to normal force. Vertical load is the load exerted on the sliding plate by the means of for example universal test machine used in this research. Normal force is the force that is compressing the sliding plate that is in between concrete blocks of sample from both sides. Sliding plate this time has been confined from both sides between blocks of concrete sample. Values for vertical load and normal force have been recorded while the sliding plate confined between two blocks of sample was being displaced downwards with constant velocity.

MTS Criterion C45 machine used for displacing sliding plate with constant velocity has various settings and one of them is preload force that was set as standard at 100N or 0.1kN. Data from the machine such as vertical load, displacement and elapsed time starts to be recorded as soon as the preload force of 0.1kN is reached. For sample 1 for an instance, it can be seen from data tables XX – XX for each of four tests. Every time the first measurement is being taken when the vertical load is around 0.1kN. Case is the same for other samples as well. Data tables corresponding to them can be reviewed in appendix B. This is explaining again that all the data acquired from the pushout test in this research is valid for kinetic coefficient of friction only.

All results from experiments using conventional method are summarized in tables 22 and 23 where the values of static and dynamic coefficients of friction respectively are presented as the mean values with their standard deviations for the different groups. The mean value of static mu for all samples is reported to be 0.30 with STD of 0.03. The mean value of kinetic mu for all samples is reported to be 0.28 with STD of 0.02. Those are the values of mu obtained from experiments using conventional method. Low values of STD indicate that data are clustered around the mean values.

All results from experiments using method of confined sliding plate are summarized in table 19 where the values of kinetic coefficients of friction are presented as the mean values with their standard deviations for the different groups. Mean value for the kinetic coefficient of friction combining all samples is reported to be 3.069 with STD of 1.277.

STD value for mu kinetic from pushout test is much higher than the one from conventional experiment: 1.277 vs 0.02. This shows that shows that data for kinetic mu obtained from pushout tests is more widely spread compared to conventional experiment where it is concentrated closely around mean value. The widespread data for kinetic mu can be seen from the tables 8 – 11 for the sample 1, where the first value of kinetic mu calculated at displacement around 0.00mm is greatly smaller that the values of kinetic mu calculated at consecutive displacement points from 2 to 30mm.

Graphs on figures 101 – 123, based on the data tables from pushout test, also show that kinetic mu increases greatly during the first displacement of first 1 mm. In the graphs that were created as a part of this research paper, the displacement step was set to 1mm. Additional graph on figure 133 shows variation of F, Ntotal and kinetic mu vs displacement for sample 1, constructed for displacement values varying from 0.00 to 1.00mm with a step of 0.01mm. This graph serves as a proof that first low value of kinetic mu during pushout test is not an outlier. With better resolution from the graph on figure 133 it is clearly seen that kinetic mu increases from around 0.2 to 2.3 as the sliding plate is displaced 0.25mm.

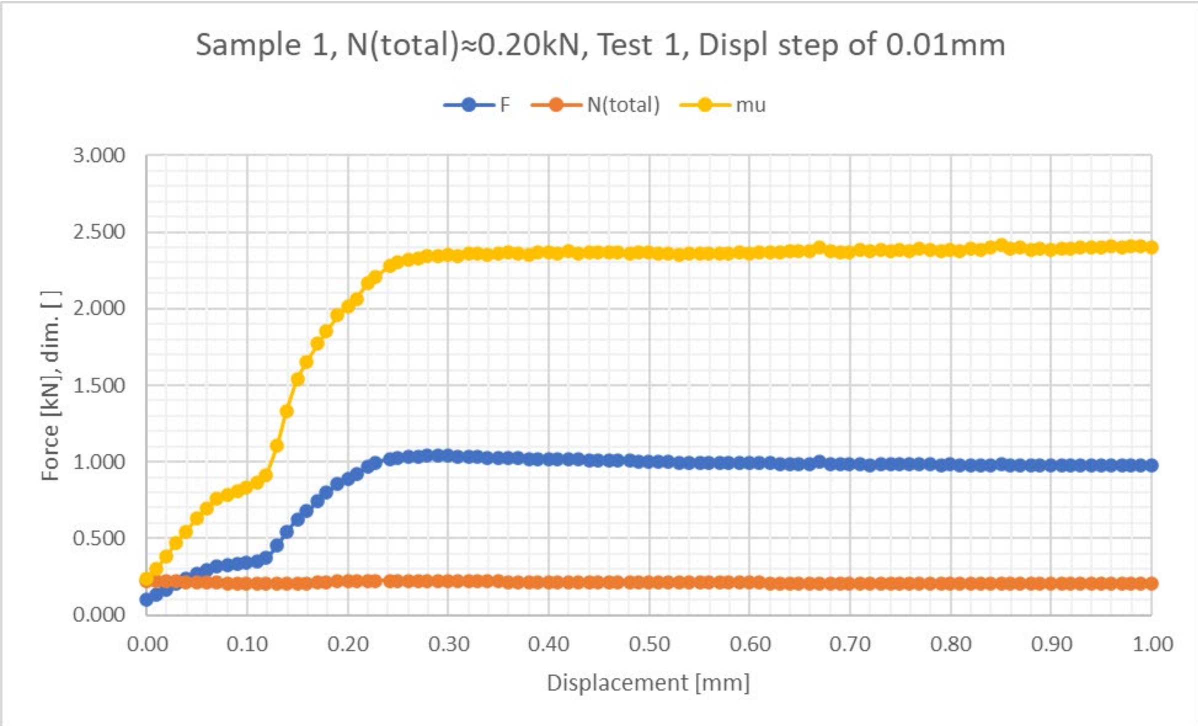


Figure 133: Sample 1, Ntotal=0.20kN, test 1, graph showing variation of F, Ntotal and mu vs displacement with displ step of 0.01mm

In the beginning of each pushout experiment, normal force has been adjusted to some specific value which did not wary much throughout experiments. Large increase in mu is therefore a result of an increase in vertical load F. Heatmaps produced in section 4.5 also show a strong correlation between kinetic mu and vertical load for all samples except sample 3.

For first two tests normal force was preset with a same value of 0.20kN to see if repeated tests are affecting results for successive trials. By looking at the graphs for the first two tests, for each sample it can be observed that for the second test mu became generally smaller. Tables 12 – 18 also prove this point. Initially preset value of normal force N was then varied for tests 3 and 4 to broaden the results matrix.

Even though the value of kinetic mu changes throughout displacement of confined sliding plate, the mean values of kinetic mu from the table 19 show that it is much higher than the one obtained from conventional experiments. Mean values for kinetic mu from conventional and pushout experiments are 0.28 and 3.069 respectively. The lowest mean kinetic mu per sample (Sample 1) from pushout experiments is still much larger than the highest mean kinetic mu per sample (Sample 3 and 6) from conventional experiments.

The roughness values for inclined steel plane used in conventional experiments were measured as well as for the sliding steel plate. Roughness of the surface is known to affect the coefficient of friction. Results were presented in tables 5 and 6. Overall mean values for roughness measurement of inclined plate and sliding plate are 0.199µm and 0.214µm respectively. Standard deviation for both measurements is the same: 0.042. Both values are very close to each other meaning that the surface roughness of inclined plate is the same as for sliding plate. This result was expected as both parts were cut from exactly the same carbon steel fabrication bar. As well as both surfaces were sanded in exactly the same way.

These results and facts are proving the hypothesis that confinement creates a higher kinetic friction coefficient compared to unconfined kinetic friction coefficient.

Reference

Aadnoy, B. S. (2006). Mechanics of Drilling (pp. 63, 64). Shaker Verlag.

Hartvigsen, H., Lorentsen, R., Michelsen, K., & Seljevoll, S. (2006). Verksted Håndboka (pp. 44, 46, 51). Gyldendal.

Industrisalg AS (2022). Skruekatalog

Appendix A

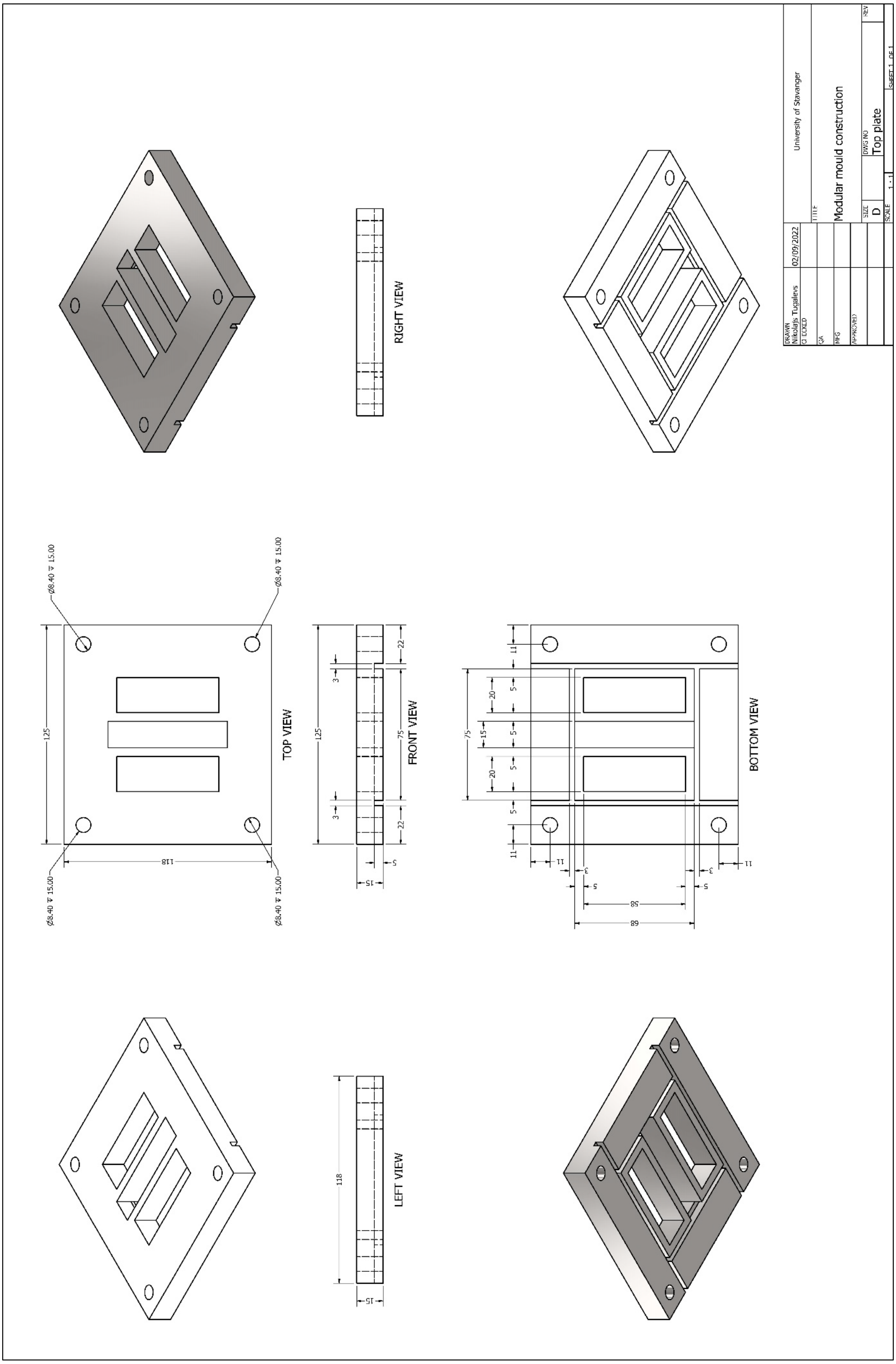


Figure 134: Sketch of the top plate created in Inventor software

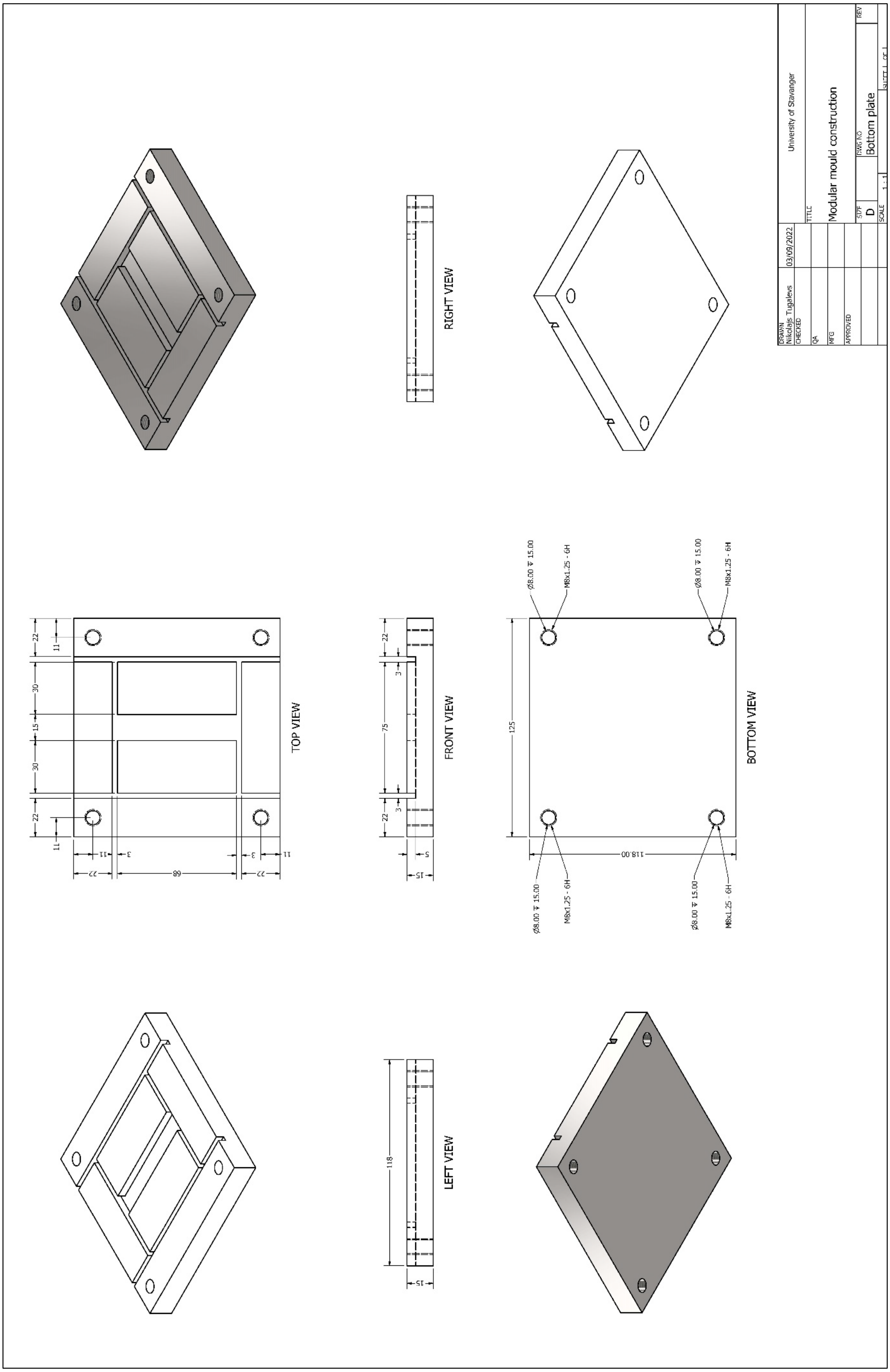


Figure 135: Sketch of the bottom plate created in Inventor software

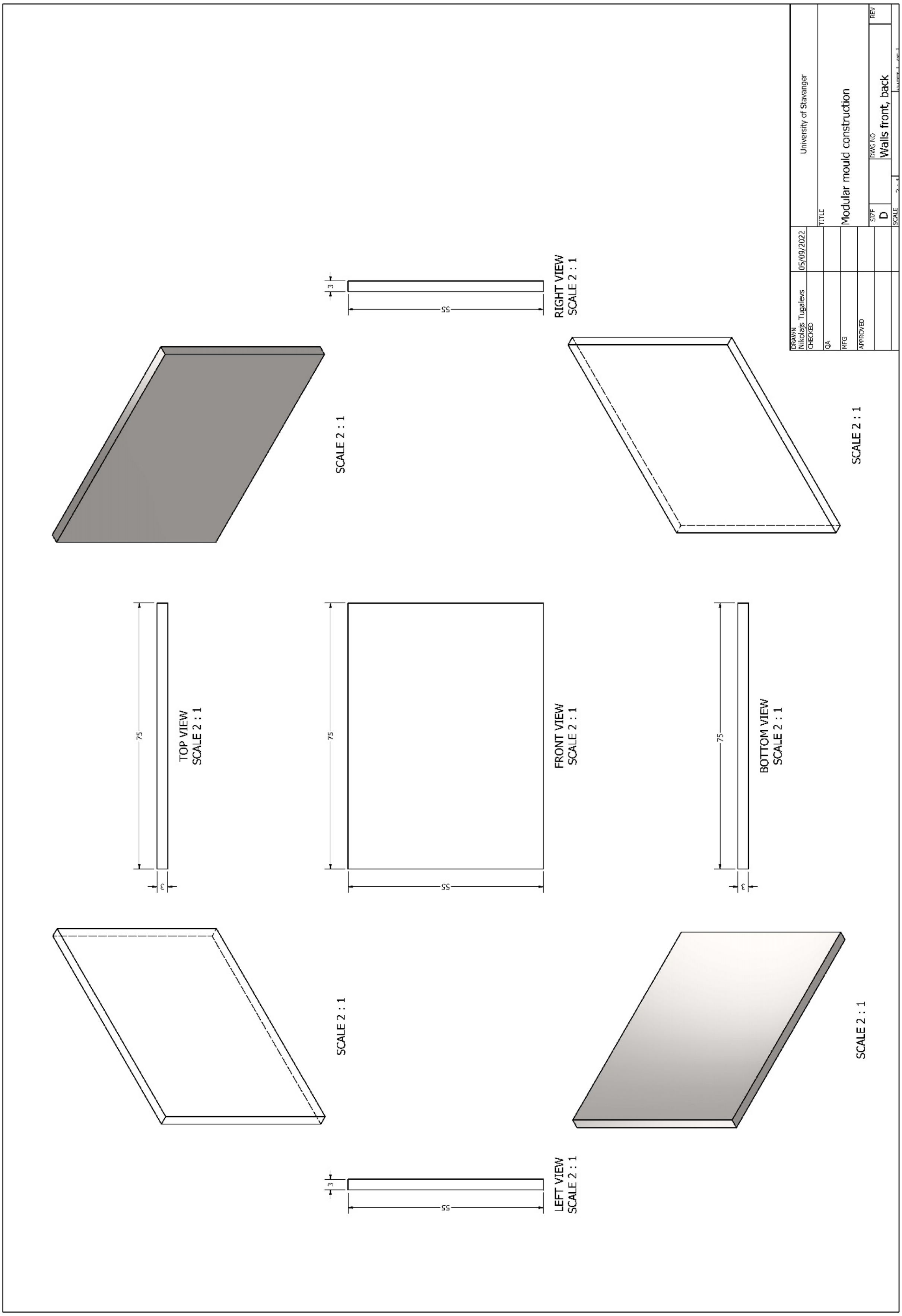


Figure 136: Sketch of the front and back wall created in Inventor software

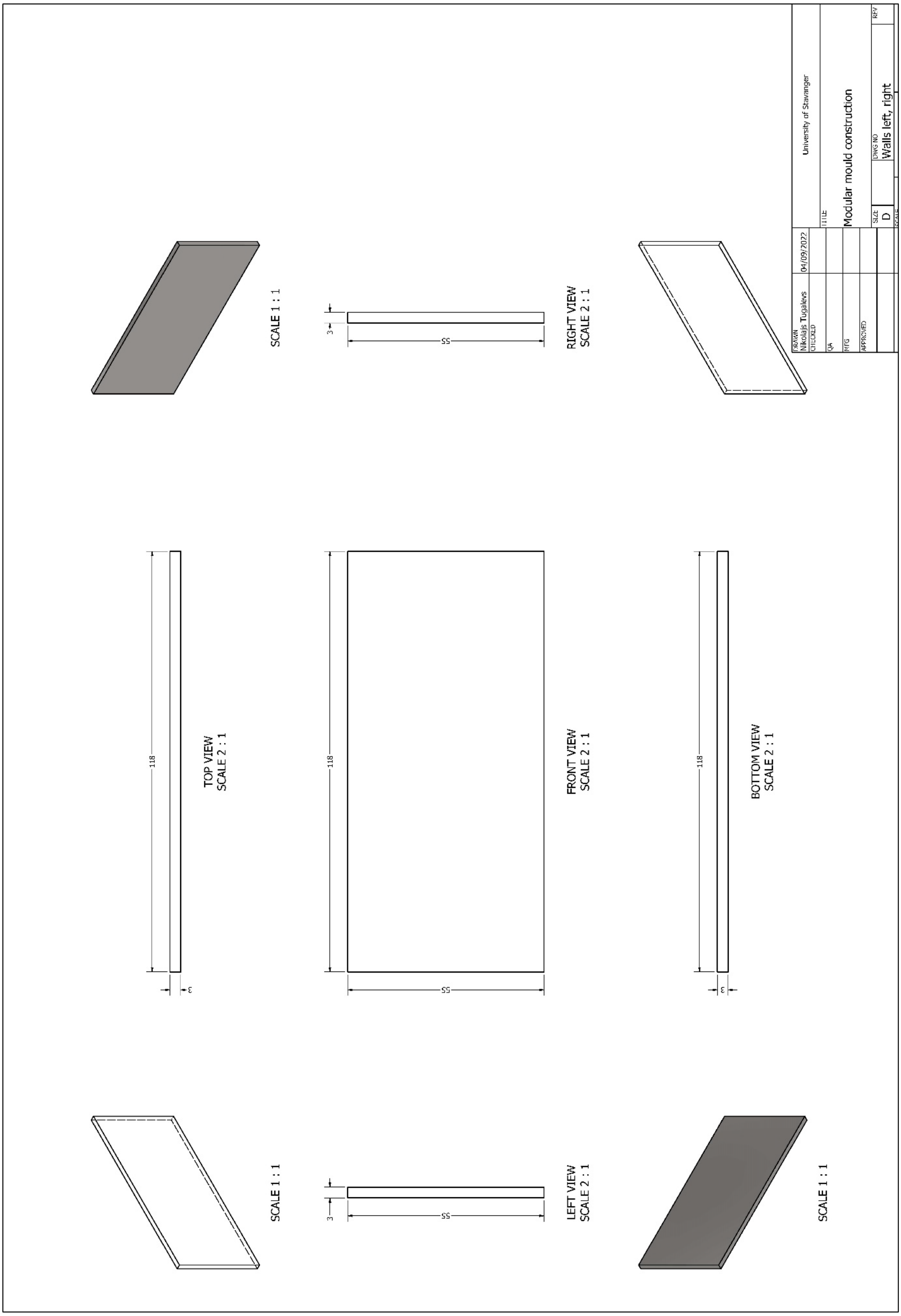


Figure 137: Sketch of the left and right wall created in Inventor software

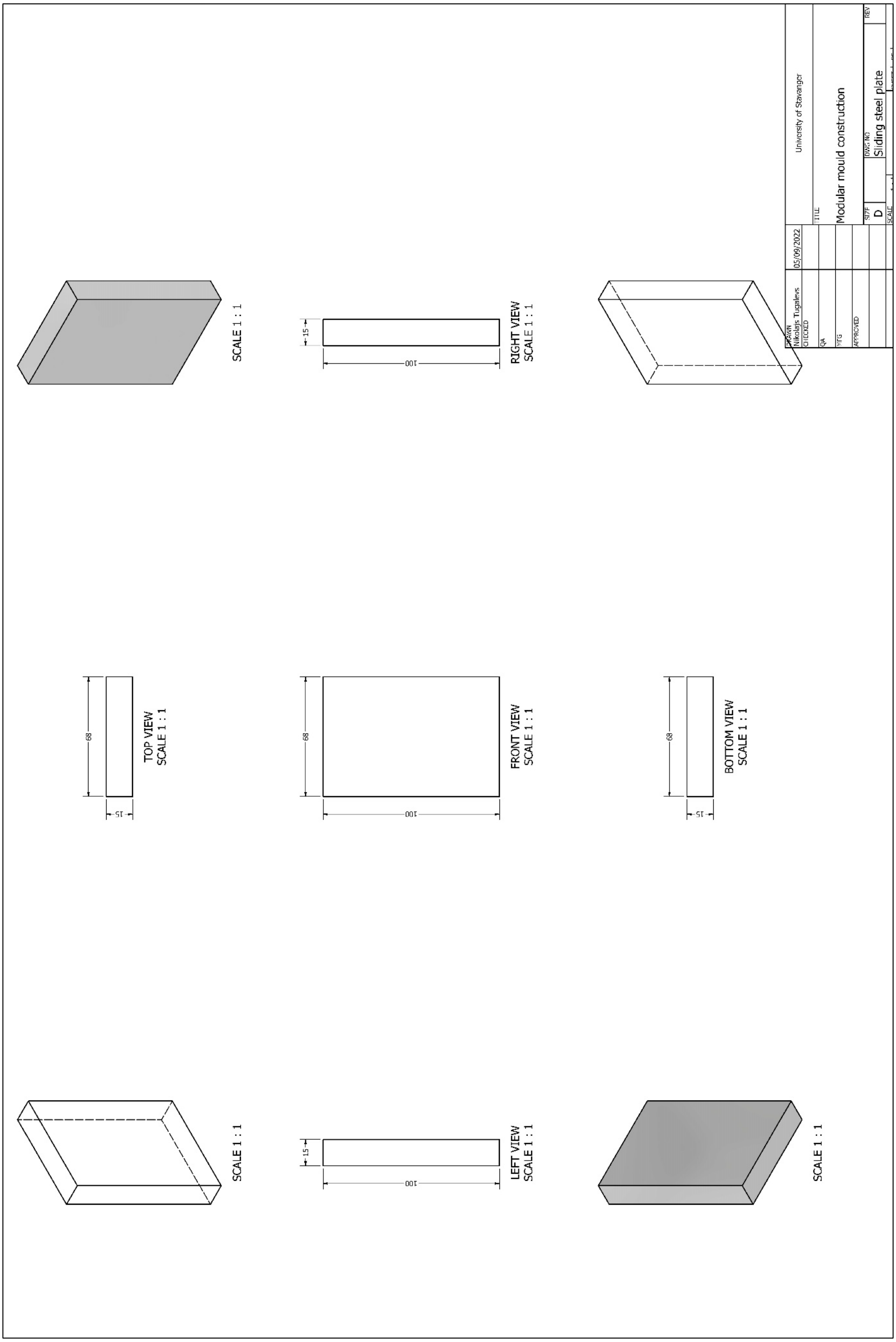


Figure 138: Sketch of the sliding plate created in Inventor software

Appendix B

Table 24: Data acquired from rectangular pushout test on sample 2 at initial Ntotal=0.20kN, test 1

Sample 2, Ntotal = 0.20kN, Test 1									
No.	Load F [kN]	Displ. [mm]	Time [s]	Voltage [V]		Normal force N [kN]			mu
				Cell 1	Cell 2	Cell 1	Cell 2	Total	
1	0.103	0.001	0.049	0.711	0.160	0.107	0.103	0.210	0.245
2	1.054	0.999	59.918	0.746	0.121	0.133	0.075	0.208	2.534
3	1.096	1.999	119.927	0.754	0.124	0.139	0.077	0.216	2.538
4	1.093	2.999	179.941	0.756	0.124	0.140	0.077	0.217	2.514
5	1.165	4.000	240.020	0.766	0.129	0.148	0.081	0.228	2.552
6	1.246	4.999	300.025	0.778	0.134	0.156	0.084	0.241	2.590
7	1.304	6.000	359.993	0.787	0.138	0.163	0.087	0.250	2.609
8	1.370	6.999	419.937	0.797	0.143	0.170	0.091	0.261	2.628
9	1.416	7.999	479.969	0.805	0.147	0.176	0.093	0.269	2.629
10	1.445	8.999	539.937	0.809	0.149	0.179	0.095	0.274	2.641
11	1.481	10.000	599.992	0.816	0.152	0.184	0.097	0.281	2.637
12	1.489	11.000	659.932	0.821	0.152	0.187	0.097	0.284	2.618
13	1.500	12.000	720.094	0.825	0.151	0.190	0.096	0.287	2.617
14	1.524	12.999	779.972	0.835	0.151	0.197	0.096	0.294	2.594
15	1.495	14.000	839.928	0.837	0.151	0.199	0.096	0.295	2.533
16	1.467	15.000	899.981	0.833	0.149	0.196	0.095	0.291	2.522
17	1.431	16.000	960.006	0.833	0.146	0.196	0.093	0.289	2.478
18	1.436	16.999	1019.890	0.830	0.144	0.194	0.091	0.285	2.518
19	1.403	18.000	1079.982	0.830	0.144	0.194	0.091	0.285	2.460
20	1.412	19.000	1140.054	0.828	0.142	0.192	0.090	0.282	2.501
21	1.393	19.999	1199.992	0.826	0.143	0.191	0.091	0.282	2.474
22	1.462	21.000	1260.003	0.834	0.145	0.197	0.092	0.289	2.532
23	1.423	21.999	1319.864	0.833	0.146	0.196	0.093	0.289	2.464
24	1.413	23.000	1379.927	0.833	0.146	0.196	0.093	0.289	2.447
25	1.249	24.000	1439.978	0.826	0.143	0.191	0.091	0.282	2.218
26	1.154	25.000	1500.026	0.820	0.140	0.187	0.088	0.275	2.097
27	1.115	26.000	1560.038	0.816	0.139	0.184	0.088	0.272	2.053
28	1.072	27.001	1620.046	0.813	0.129	0.182	0.081	0.262	2.044
29	1.140	28.000	1680.023	0.810	0.126	0.179	0.079	0.258	2.210
30	1.063	29.001	1740.010	0.808	0.125	0.178	0.078	0.256	2.078
31	1.112	29.999	1799.968	0.807	0.120	0.177	0.074	0.252	2.210

Table 25: Data acquired from rectangular pushout test on sample 2 at initial Ntotal=0.20kN, test 2

Sample 2, Ntotal = 0.20kN, Test 2									
No.	Load F [kN]	Displ. [mm]	Time [s]	Voltage [V]		Normal force N [kN]			mu
				Cell 1	Cell 2	Cell 1	Cell 2	Total	
1	0.104	0.001	0.066	0.718	0.166	0.112	0.107	0.219	0.237
2	0.933	1.000	60.037	0.830	0.301	0.194	0.205	0.399	1.168
3	1.085	2.000	119.967	0.860	0.362	0.215	0.251	0.466	1.163
4	1.416	2.999	179.824	0.930	0.490	0.265	0.349	0.614	1.153
5	1.207	4.000	239.983	0.898	0.449	0.242	0.317	0.560	1.078
6	1.236	5.000	299.975	0.898	0.447	0.242	0.316	0.558	1.107
7	1.231	6.000	359.976	0.898	0.446	0.242	0.315	0.557	1.104
8	1.272	6.999	419.919	0.898	0.446	0.242	0.315	0.557	1.141
9	1.246	8.000	480.003	0.896	0.447	0.241	0.316	0.557	1.119
10	1.301	9.000	539.920	0.896	0.450	0.241	0.318	0.559	1.164
11	1.329	9.999	599.901	0.898	0.459	0.242	0.325	0.567	1.171
12	1.261	11.000	660.016	0.904	0.478	0.247	0.340	0.586	1.075
13	1.436	11.999	719.891	0.910	0.495	0.251	0.353	0.604	1.189
14	1.411	12.999	779.912	0.912	0.508	0.252	0.363	0.615	1.146
15	1.472	14.000	839.985	0.917	0.524	0.256	0.376	0.631	1.165
16	1.447	15.000	899.983	0.920	0.540	0.258	0.388	0.646	1.120
17	1.479	15.999	959.926	0.925	0.552	0.261	0.398	0.659	1.122
18	1.613	17.000	1020.055	0.928	0.560	0.263	0.404	0.668	1.208
19	1.632	18.000	1080.010	0.933	0.569	0.267	0.411	0.678	1.203
20	1.537	19.000	1140.010	0.934	0.576	0.268	0.417	0.685	1.123
21	1.647	20.000	1199.987	0.937	0.584	0.270	0.423	0.693	1.188
22	1.664	20.999	1259.889	0.944	0.600	0.275	0.436	0.711	1.171
23	1.623	22.000	1319.983	0.947	0.606	0.277	0.441	0.718	1.131
24	1.667	22.999	1379.928	0.947	0.608	0.277	0.442	0.719	1.159
25	1.546	24.000	1440.002	0.948	0.608	0.278	0.442	0.720	1.074
26	1.624	24.999	1499.917	0.946	0.609	0.276	0.443	0.719	1.129
27	1.692	25.999	1559.936	0.945	0.610	0.275	0.444	0.719	1.176
28	1.713	27.001	1620.078	0.943	0.613	0.274	0.446	0.720	1.189
29	1.630	28.000	1680.005	0.939	0.611	0.271	0.445	0.716	1.138
30	1.769	28.999	1739.939	0.933	0.610	0.267	0.444	0.711	1.244
31	1.589	30.000	1800.046	0.926	0.607	0.262	0.442	0.704	1.129

Table 26: Data acquired from rectangular pushout test on sample 2 at initial Ntotal=0.10kN, test 3

Sample 2, Ntotal = 0.10kN, Test 3									
No.	Load F [kN]	Displ. [mm]	Time [s]	Voltage [V]		Normal force N [kN]			mu
				Cell 1	Cell 2	Cell 1	Cell 2	Total	
1	0.100	0.001	0.103	0.640	0.076	0.054	0.043	0.097	0.514
2	1.257	0.999	59.949	0.657	0.106	0.067	0.064	0.131	4.789
3	1.314	2.000	119.943	0.661	0.110	0.070	0.067	0.137	4.793
4	1.240	3.000	180.006	0.662	0.114	0.071	0.070	0.141	4.408
5	1.302	3.999	239.914	0.666	0.117	0.074	0.072	0.146	4.466
6	1.322	4.999	299.890	0.669	0.120	0.076	0.074	0.150	4.402
7	1.365	5.999	359.969	0.671	0.123	0.077	0.076	0.154	4.438
8	1.313	6.999	419.926	0.676	0.127	0.081	0.079	0.160	4.094
9	1.390	7.999	479.978	0.677	0.130	0.082	0.081	0.163	4.258
10	1.474	9.000	540.042	0.683	0.137	0.086	0.086	0.173	4.268
11	1.561	10.000	600.046	0.687	0.141	0.089	0.089	0.179	4.372
12	1.633	11.000	660.025	0.687	0.143	0.089	0.091	0.180	4.537
13	1.696	11.999	719.907	0.690	0.146	0.092	0.093	0.184	4.601
14	1.699	13.000	780.054	0.693	0.149	0.094	0.095	0.189	4.502
15	1.763	13.999	839.925	0.696	0.152	0.096	0.097	0.193	4.566
16	1.677	14.999	899.989	0.699	0.155	0.098	0.099	0.197	4.247
17	1.717	15.999	959.948	0.701	0.157	0.100	0.101	0.200	4.285
18	1.766	17.000	1019.996	0.706	0.162	0.104	0.104	0.208	4.252
19	1.977	18.000	1079.972	0.708	0.165	0.105	0.106	0.211	4.679
20	1.803	18.999	1139.941	0.713	0.170	0.109	0.110	0.219	4.125
21	1.936	19.999	1200.009	0.713	0.171	0.109	0.111	0.219	4.414
22	1.882	21.000	1259.998	0.715	0.174	0.110	0.113	0.223	4.221
23	2.006	22.000	1320.008	0.719	0.179	0.113	0.116	0.229	4.371
24	2.074	22.999	1380.008	0.719	0.182	0.113	0.119	0.232	4.477
25	2.088	23.999	1439.958	0.721	0.185	0.115	0.121	0.235	4.438
26	2.220	24.999	1499.945	0.721	0.189	0.115	0.124	0.238	4.661
27	2.258	25.999	1560.020	0.721	0.193	0.115	0.126	0.241	4.684
28	2.194	27.000	1619.950	0.721	0.196	0.115	0.129	0.243	4.511
29	2.270	27.999	1679.916	0.720	0.198	0.114	0.130	0.244	4.654
30	2.135	29.000	1739.966	0.721	0.204	0.115	0.134	0.249	4.287
31	2.236	30.000	1800.058	0.720	0.202	0.114	0.133	0.247	4.530

Table 27: Data acquired from rectangular pushout test on sample 2 at initial Ntotal=0.30kN, test 4

Sample 2, Ntotal = 0.30kN, Test 4									
No.	Load F [kN]	Displ. [mm]	Time [s]	Voltage [V]		Normal force N [kN]			mu
				Cell 1	Cell 2	Cell 1	Cell 2	Total	
1	0.099	0.000	0.061	0.766	0.225	0.148	0.150	0.297	0.167
2	1.548	1.000	60.003	0.795	0.148	0.169	0.094	0.263	2.945
3	1.672	2.000	120.016	0.800	0.146	0.172	0.093	0.265	3.155
4	1.681	2.999	179.938	0.807	0.144	0.177	0.091	0.269	3.129
5	1.687	4.000	239.982	0.813	0.147	0.182	0.093	0.275	3.067
6	1.741	5.000	300.031	0.821	0.153	0.187	0.098	0.285	3.053
7	2.006	6.000	359.983	0.833	0.157	0.196	0.101	0.297	3.382
8	1.981	6.999	419.947	0.843	0.159	0.203	0.102	0.305	3.246
9	2.254	8.000	479.976	0.854	0.167	0.211	0.108	0.319	3.536
10	2.350	8.999	539.923	0.863	0.176	0.217	0.114	0.332	3.543
11	2.315	9.999	600.013	0.873	0.184	0.225	0.120	0.344	3.360
12	2.497	10.999	659.944	0.882	0.199	0.231	0.131	0.362	3.452
13	2.651	11.999	719.835	0.890	0.213	0.237	0.141	0.378	3.511
14	2.607	13.001	780.006	0.898	0.230	0.242	0.153	0.396	3.295
15	2.704	13.999	839.886	0.905	0.247	0.247	0.166	0.413	3.274
16	2.948	15.000	900.001	0.911	0.264	0.251	0.178	0.430	3.431
17	2.915	16.001	960.053	0.916	0.276	0.255	0.187	0.442	3.298
18	3.123	17.001	1020.080	0.922	0.291	0.259	0.198	0.457	3.415
19	3.155	18.001	1080.043	0.929	0.303	0.264	0.207	0.471	3.348
20	3.219	19.000	1139.990	0.934	0.316	0.268	0.217	0.484	3.323
21	3.339	20.001	1200.058	0.939	0.327	0.271	0.225	0.496	3.365
22	3.317	21.000	1260.005	0.943	0.335	0.274	0.231	0.505	3.285
23	3.304	22.000	1319.912	0.945	0.339	0.275	0.234	0.509	3.244
24	3.439	23.000	1379.988	0.946	0.340	0.276	0.235	0.511	3.367
25	3.323	24.001	1439.998	0.946	0.341	0.276	0.235	0.511	3.248
26	3.416	25.000	1500.011	0.947	0.342	0.277	0.236	0.513	3.330
27	3.348	26.001	1560.045	0.948	0.352	0.278	0.244	0.521	3.212
28	3.437	27.000	1619.926	0.948	0.356	0.278	0.247	0.524	3.279
29	3.577	28.000	1679.903	0.948	0.361	0.278	0.250	0.528	3.388
30	3.440	29.000	1739.996	0.946	0.364	0.276	0.253	0.529	3.253
31	3.397	29.999	1799.943	0.954	0.399	0.282	0.279	0.561	3.028

Table 28: Data acquired from rectangular pushout test on sample 3 at initial Ntotal=0.20kN, test 1

Sample 3, Ntotal = 0.20kN, Test 1									
No.	Load F [kN]	Displ. [mm]	Time [s]	Voltage [V]		Normal force N [kN]			mu
				Cell 1	Cell 2	Cell 1	Cell 2	Total	
1	0.101	0.001	0.074	0.712	0.173	0.108	0.112	0.220	0.230
2	1.209	1.000	59.994	0.699	0.135	0.098	0.085	0.183	3.300
3	1.326	2.001	120.030	0.705	0.146	0.103	0.093	0.195	3.392
4	1.404	3.000	180.022	0.708	0.160	0.105	0.103	0.208	3.380
5	1.452	4.000	239.995	0.712	0.171	0.108	0.111	0.219	3.322
6	1.470	5.000	299.998	0.713	0.180	0.109	0.117	0.226	3.256
7	1.527	6.000	360.030	0.715	0.179	0.110	0.116	0.227	3.371
8	1.650	7.001	420.088	0.716	0.192	0.111	0.126	0.237	3.487
9	1.760	8.001	480.016	0.723	0.208	0.116	0.137	0.253	3.473
10	1.921	9.001	540.051	0.729	0.225	0.121	0.150	0.270	3.556
11	2.047	10.000	600.033	0.735	0.239	0.125	0.160	0.285	3.594
12	2.197	11.000	660.021	0.743	0.259	0.131	0.174	0.305	3.599
13	2.343	12.000	719.923	0.750	0.279	0.136	0.189	0.325	3.603
14	2.493	13.000	779.977	0.758	0.299	0.142	0.204	0.346	3.605
15	2.618	14.001	840.088	0.764	0.315	0.146	0.216	0.362	3.616
16	2.753	15.000	900.025	0.772	0.332	0.152	0.229	0.381	3.617
17	2.862	16.000	959.982	0.781	0.351	0.159	0.243	0.401	3.565
18	2.941	17.001	1020.025	0.794	0.372	0.168	0.259	0.427	3.447
19	3.065	18.001	1080.023	0.795	0.375	0.169	0.261	0.430	3.567
20	3.105	19.001	1140.023	0.803	0.388	0.174	0.271	0.445	3.487
21	3.135	20.001	1200.019	0.809	0.396	0.179	0.277	0.456	3.440
22	3.133	21.000	1259.988	0.819	0.407	0.186	0.285	0.471	3.324
23	3.174	22.001	1320.041	0.824	0.413	0.190	0.290	0.479	3.311
24	3.202	23.000	1379.986	0.822	0.408	0.188	0.286	0.474	3.377
25	3.171	24.000	1439.991	0.828	0.413	0.192	0.290	0.482	3.288
26	3.146	25.001	1500.053	0.832	0.417	0.195	0.293	0.488	3.222
27	3.209	26.001	1560.029	0.832	0.414	0.195	0.291	0.486	3.302
28	3.073	27.001	1620.043	0.835	0.423	0.197	0.297	0.495	3.105
29	3.099	28.000	1679.999	0.834	0.421	0.197	0.296	0.493	3.145
30	3.094	29.000	1740.047	0.840	0.415	0.201	0.291	0.492	3.142
31	3.063	29.999	1799.933	0.839	0.408	0.200	0.286	0.486	3.149

Table 29: Data acquired from rectangular pushout test on sample 3 at initial Ntotal=0.20kN, test 2

Sample 3, Ntotal = 0.20kN, Test 2									
No.	Load F [kN]	Displ. [mm]	Time [s]	Voltage [V]		Normal force N [kN]			mu
				Cell 1	Cell 2	Cell 1	Cell 2	Total	
1	0.990	0.000	0.052	0.713	0.173	0.109	0.112	0.221	2.243
2	1.133	1.001	60.034	0.702	0.178	0.101	0.116	0.216	2.621
3	1.207	2.001	120.047	0.706	0.186	0.104	0.121	0.225	2.684
4	1.263	3.000	179.997	0.708	0.190	0.105	0.124	0.229	2.755
5	1.342	4.001	239.989	0.709	0.193	0.106	0.126	0.232	2.890
6	1.351	5.001	300.039	0.711	0.195	0.107	0.128	0.235	2.873
7	1.329	6.000	359.979	0.712	0.196	0.108	0.129	0.237	2.809
8	1.434	7.000	419.975	0.713	0.200	0.109	0.131	0.240	2.985
9	1.480	8.001	480.044	0.715	0.203	0.110	0.134	0.244	3.035
10	1.547	9.001	540.037	0.717	0.205	0.112	0.135	0.247	3.135
11	1.565	10.000	599.979	0.720	0.208	0.114	0.137	0.251	3.116
12	1.624	11.000	660.040	0.722	0.210	0.115	0.139	0.254	3.196
13	1.616	12.000	719.923	0.720	0.201	0.114	0.132	0.246	3.284
14	1.673	13.000	779.982	0.719	0.200	0.113	0.131	0.245	3.420
15	1.642	14.001	840.042	0.720	0.201	0.114	0.132	0.246	3.336
16	1.724	15.000	899.999	0.721	0.201	0.115	0.132	0.247	3.493
17	1.787	16.001	960.033	0.721	0.203	0.115	0.134	0.248	3.599
18	1.683	17.000	1019.987	0.721	0.204	0.115	0.134	0.249	3.380
19	1.709	18.001	1080.047	0.723	0.204	0.116	0.134	0.250	3.412
20	1.775	19.001	1140.042	0.723	0.205	0.116	0.135	0.251	3.533
21	1.714	20.001	1200.045	0.725	0.203	0.118	0.134	0.251	3.412
22	1.640	21.000	1259.995	0.725	0.203	0.118	0.134	0.251	3.264
23	1.629	22.000	1320.033	0.727	0.201	0.119	0.132	0.251	3.242
24	1.565	22.999	1379.974	0.728	0.201	0.120	0.132	0.252	3.106
25	1.570	24.001	1439.966	0.730	0.201	0.121	0.132	0.253	3.097
26	1.608	25.001	1500.038	0.732	0.203	0.123	0.134	0.256	3.136
27	1.571	26.000	1560.038	0.734	0.203	0.124	0.134	0.258	3.047
28	1.573	27.001	1620.039	0.734	0.204	0.124	0.134	0.259	3.042
29	1.544	28.001	1680.048	0.734	0.203	0.124	0.134	0.258	2.994
30	1.548	29.000	1739.934	0.735	0.202	0.125	0.133	0.258	3.002
31	1.511	29.998	1799.848	0.736	0.201	0.126	0.132	0.258	2.930

Table 30: Data acquired from rectangular pushout test on sample 3 at initial Ntotal=0.10kN, test 3

Sample 3, Ntotal = 0.10kN, Test 3									
No.	Load F [kN]	Displ. [mm]	Time [s]	Voltage [V]		Normal force N [kN]			mu
				Cell 1	Cell 2	Cell 1	Cell 2	Total	
1	0.102	0.001	0.063	0.641	0.090	0.055	0.053	0.108	0.473
2	0.549	1.000	59.945	0.662	0.111	0.071	0.068	0.139	1.982
3	0.530	2.001	119.969	0.664	0.113	0.072	0.069	0.141	1.874
4	0.586	3.000	179.964	0.667	0.117	0.074	0.072	0.147	2.000
5	0.609	4.000	239.970	0.670	0.120	0.077	0.074	0.151	2.018
6	0.644	5.001	300.059	0.674	0.124	0.080	0.077	0.157	2.054
7	0.657	6.000	359.947	0.679	0.128	0.083	0.080	0.163	2.011
8	0.715	7.000	419.995	0.680	0.132	0.084	0.083	0.167	2.142
9	0.721	8.001	479.987	0.684	0.137	0.087	0.086	0.173	2.079
10	0.717	9.000	540.045	0.687	0.141	0.089	0.089	0.179	2.008
11	0.717	10.001	600.015	0.689	0.143	0.091	0.091	0.181	1.976
12	0.783	11.001	660.051	0.690	0.146	0.092	0.093	0.184	2.124
13	0.825	12.001	720.049	0.693	0.150	0.094	0.096	0.189	2.178
14	0.850	13.000	779.918	0.694	0.152	0.095	0.097	0.192	2.218
15	0.892	14.001	840.092	0.695	0.156	0.095	0.100	0.195	2.285
16	0.911	15.001	900.066	0.697	0.158	0.097	0.101	0.198	2.299
17	0.913	16.001	960.004	0.699	0.162	0.098	0.104	0.202	2.255
18	0.950	17.000	1019.975	0.701	0.165	0.100	0.106	0.206	2.305
19	0.971	18.001	1080.039	0.702	0.168	0.101	0.108	0.209	2.323
20	1.002	19.001	1140.032	0.703	0.172	0.101	0.111	0.213	2.357
21	1.017	20.001	1200.044	0.705	0.173	0.103	0.112	0.215	2.367
22	1.008	21.001	1260.035	0.705	0.176	0.103	0.114	0.217	2.323
23	1.019	21.999	1319.993	0.707	0.178	0.104	0.116	0.220	2.317
24	1.021	23.001	1380.051	0.709	0.180	0.106	0.117	0.223	2.291
25	1.096	24.001	1440.042	0.709	0.183	0.106	0.119	0.225	2.436
26	1.094	25.000	1500.012	0.711	0.186	0.107	0.121	0.229	2.393
27	1.059	26.001	1559.961	0.712	0.191	0.108	0.125	0.233	2.273
28	1.145	27.001	1620.046	0.713	0.193	0.109	0.126	0.235	2.435
29	1.079	28.001	1680.052	0.715	0.197	0.110	0.129	0.239	2.253
30	1.157	29.001	1740.007	0.716	0.200	0.111	0.131	0.242	2.387
31	1.180	29.999	1799.936	0.717	0.204	0.112	0.134	0.246	2.398

Table 31: Data acquired from rectangular pushout test on sample 3 at initial Ntotal=0.30kN, test 4

Sample 3, Ntotal = 0.30kN, Test 4									
No.	Load F [kN]	Displ. [mm]	Time [s]	Voltage [V]		Normal force N [kN]			mu
				Cell 1	Cell 2	Cell 1	Cell 2	Total	
1	0.098	0.000	0.042	0.768	0.225	0.149	0.150	0.299	0.164
2	1.439	1.000	59.929	0.762	0.184	0.145	0.120	0.265	2.719
3	1.574	2.001	119.986	0.765	0.186	0.147	0.121	0.268	2.934
4	1.715	3.000	179.984	0.770	0.189	0.151	0.124	0.274	3.129
5	1.814	3.999	239.961	0.775	0.189	0.154	0.124	0.278	3.266
6	1.898	5.001	300.055	0.781	0.190	0.159	0.124	0.283	3.356
7	1.974	6.000	359.980	0.788	0.190	0.164	0.124	0.288	3.429
8	2.056	7.000	419.982	0.796	0.190	0.169	0.124	0.294	3.501
9	2.140	8.000	479.959	0.804	0.189	0.175	0.124	0.299	3.582
10	2.326	9.001	540.059	0.816	0.188	0.184	0.123	0.307	3.793
11	2.306	10.001	599.984	0.829	0.187	0.193	0.122	0.315	3.658
12	2.420	11.000	660.040	0.842	0.188	0.202	0.123	0.325	3.720
13	2.484	12.000	720.040	0.853	0.189	0.210	0.124	0.334	3.720
14	2.636	13.001	779.967	0.867	0.191	0.220	0.125	0.345	3.817
15	2.750	14.000	839.981	0.880	0.192	0.230	0.126	0.355	3.871
16	2.772	14.999	899.954	0.893	0.194	0.239	0.127	0.366	3.788
17	2.883	16.000	959.993	0.906	0.195	0.248	0.128	0.376	3.836
18	3.035	17.000	1019.996	0.915	0.194	0.254	0.127	0.381	3.978
19	3.084	18.000	1080.029	0.927	0.194	0.263	0.127	0.390	3.955
20	3.215	19.001	1140.092	0.940	0.195	0.272	0.128	0.400	4.021
21	3.260	20.000	1199.958	0.952	0.196	0.280	0.129	0.409	3.986
22	3.282	21.001	1260.034	0.960	0.195	0.286	0.128	0.414	3.965
23	3.346	21.999	1319.979	0.971	0.196	0.294	0.129	0.422	3.962
24	3.502	23.000	1380.050	0.979	0.199	0.299	0.131	0.430	4.072
25	3.628	24.000	1440.033	0.990	0.203	0.307	0.134	0.441	4.117
26	3.735	25.000	1499.952	0.996	0.208	0.311	0.137	0.448	4.164
27	3.698	26.000	1559.984	1.008	0.212	0.320	0.140	0.460	4.022
28	3.933	27.000	1620.033	1.013	0.217	0.323	0.144	0.467	4.212
29	3.945	28.001	1679.956	1.024	0.222	0.331	0.147	0.478	4.125
30	3.910	29.001	1740.111	1.026	0.225	0.332	0.150	0.482	4.058
31	4.128	29.999	1799.869	1.030	0.229	0.335	0.153	0.487	4.234

Table 32: Data acquired from rectangular pushout test on sample 4 at initial Ntotal=0.20kN, test 1

Sample 4, Ntotal = 0.20kN, Test 1									
No.	Load F [kN]	Displ. [mm]	Time [s]	Voltage [V]		Normal force N [kN]			mu
				Cell 1	Cell 2	Cell 1	Cell 2	Total	
1	0.099	0.001	0.039	0.712	0.181	0.108	0.118	0.226	0.219
2	1.745	1.000	60.046	0.736	0.227	0.126	0.151	0.277	3.153
3	1.903	2.001	120.035	0.731	0.225	0.122	0.150	0.272	3.503
4	1.922	3.000	180.018	0.732	0.234	0.123	0.156	0.279	3.446
5	2.000	4.000	239.969	0.732	0.231	0.123	0.154	0.277	3.614
6	2.110	5.000	300.012	0.734	0.241	0.124	0.161	0.285	3.696
7	2.184	6.000	360.017	0.737	0.247	0.126	0.166	0.292	3.739
8	2.288	7.000	420.020	0.742	0.259	0.130	0.174	0.305	3.757
9	2.368	8.001	480.080	0.745	0.267	0.132	0.180	0.313	3.787
10	2.425	9.000	539.979	0.750	0.274	0.136	0.186	0.321	3.772
11	2.497	10.000	600.016	0.754	0.284	0.139	0.193	0.332	3.764
12	2.490	11.001	660.073	0.761	0.299	0.144	0.204	0.348	3.578
13	2.536	12.001	720.098	0.764	0.294	0.146	0.200	0.346	3.660
14	2.566	13.001	780.027	0.766	0.293	0.148	0.200	0.347	3.696
15	2.645	14.000	840.014	0.768	0.293	0.149	0.200	0.349	3.794
16	2.541	15.000	899.986	0.770	0.292	0.151	0.199	0.349	3.637
17	2.679	16.000	959.934	0.773	0.291	0.153	0.198	0.351	3.819
18	2.729	17.000	1020.019	0.776	0.292	0.155	0.199	0.354	3.858
19	2.611	18.001	1080.023	0.779	0.265	0.157	0.179	0.336	3.886
20	2.643	19.001	1140.003	0.779	0.263	0.157	0.177	0.334	3.951
21	2.681	20.000	1200.085	0.778	0.261	0.156	0.176	0.332	4.034
22	2.592	21.000	1259.992	0.777	0.261	0.156	0.176	0.332	3.909
23	2.481	22.000	1319.978	0.776	0.262	0.155	0.177	0.332	3.741
24	2.662	23.000	1380.025	0.774	0.263	0.153	0.177	0.331	4.023
25	2.592	24.000	1439.952	0.773	0.263	0.153	0.177	0.330	3.926
26	2.666	25.001	1500.079	0.772	0.265	0.152	0.179	0.331	4.029
27	2.567	26.000	1559.987	0.772	0.266	0.152	0.180	0.332	3.871
28	2.582	27.001	1619.996	0.772	0.275	0.152	0.186	0.338	3.817
29	2.630	28.000	1679.985	0.771	0.273	0.151	0.185	0.336	3.914
30	2.462	29.001	1740.080	0.770	0.272	0.151	0.184	0.335	3.680
31	2.545	30.000	1800.024	0.769	0.269	0.150	0.182	0.332	3.837

Table 33: Data acquired from rectangular pushout test on sample 4 at initial Ntotal=0.20kN, test 2

Sample 4, Ntotal = 0.20kN, Test 2									
No.	Load F [kN]	Displ. [mm]	Time [s]	Voltage [V]		Normal force N [kN]			mu
				Cell 1	Cell 2	Cell 1	Cell 2	Total	
1	0.103	0.001	0.094	0.714	0.180	0.109	0.117	0.226	0.227
2	1.024	1.000	60.054	0.731	0.216	0.122	0.143	0.265	1.932
3	1.112	2.001	120.090	0.739	0.230	0.128	0.153	0.281	1.978
4	1.183	3.001	180.045	0.746	0.245	0.133	0.164	0.297	1.990
5	1.253	4.001	239.999	0.751	0.256	0.137	0.172	0.309	2.028
6	1.334	5.000	300.012	0.753	0.263	0.138	0.177	0.316	2.114
7	1.397	6.000	360.180	0.757	0.269	0.141	0.182	0.323	2.163
8	1.399	7.000	419.995	0.758	0.273	0.142	0.185	0.327	2.142
9	1.452	8.000	480.004	0.758	0.273	0.142	0.185	0.327	2.223
10	1.497	9.000	539.969	0.758	0.276	0.142	0.187	0.329	2.277
11	1.530	10.000	599.989	0.760	0.283	0.143	0.192	0.335	2.281
12	1.548	11.000	659.996	0.761	0.289	0.144	0.197	0.341	2.273
13	1.558	12.001	719.992	0.764	0.303	0.146	0.207	0.353	2.206
14	1.570	13.000	779.967	0.762	0.303	0.145	0.207	0.352	2.232
15	1.553	14.001	840.079	0.761	0.306	0.144	0.209	0.353	2.199
16	1.585	15.001	900.106	0.761	0.311	0.144	0.213	0.357	2.221
17	1.608	16.001	960.020	0.760	0.317	0.143	0.217	0.361	2.230
18	1.625	17.000	1020.017	0.759	0.320	0.142	0.220	0.362	2.244
19	1.651	18.000	1080.058	0.759	0.325	0.142	0.223	0.366	2.256
20	1.705	19.001	1140.019	0.758	0.331	0.142	0.228	0.370	2.307
21	1.718	20.001	1200.010	0.759	0.337	0.142	0.232	0.375	2.292
22	1.762	21.000	1259.960	0.759	0.343	0.142	0.237	0.379	2.323
23	1.707	22.000	1320.018	0.759	0.357	0.142	0.247	0.390	2.189
24	1.765	23.000	1379.955	0.758	0.360	0.142	0.250	0.391	2.255
25	1.745	24.000	1440.020	0.759	0.366	0.142	0.254	0.397	2.200
26	1.781	25.001	1500.073	0.759	0.367	0.142	0.255	0.397	2.241
27	1.848	26.001	1560.066	0.758	0.369	0.142	0.256	0.398	2.321
28	1.848	27.000	1620.011	0.758	0.369	0.142	0.256	0.398	2.321
29	1.885	28.000	1679.961	0.758	0.370	0.142	0.257	0.399	2.363
30	1.923	29.000	1740.019	0.759	0.373	0.142	0.259	0.402	2.392
31	1.962	30.000	1799.994	0.759	0.376	0.142	0.262	0.404	2.427

Table 34: Data acquired from rectangular pushout test on sample 4 at initial Ntotal=0.10kN, test 3

Sample 4, Ntotal = 0.10kN, Test 3									
No.	Load F [kN]	Displ. [mm]	Time [s]	Voltage [V]		Normal force N [kN]			mu
				Cell 1	Cell 2	Cell 1	Cell 2	Total	
1	0.098	0.000	0.104	0.646	0.085	0.059	0.050	0.108	0.453
2	0.334	1.000	60.015	0.659	0.091	0.068	0.054	0.122	1.367
3	0.339	2.000	119.997	0.671	0.098	0.077	0.059	0.136	1.245
4	0.353	3.000	180.020	0.680	0.104	0.084	0.063	0.147	1.200
5	0.393	4.000	240.031	0.684	0.105	0.087	0.064	0.151	1.303
6	0.407	5.001	300.111	0.688	0.107	0.090	0.065	0.155	1.311
7	0.469	6.001	360.034	0.695	0.110	0.095	0.067	0.163	1.443
8	0.508	7.001	420.089	0.702	0.113	0.101	0.069	0.170	1.496
9	0.583	8.001	480.066	0.709	0.116	0.106	0.071	0.177	1.645
10	0.613	9.000	539.994	0.714	0.119	0.109	0.074	0.183	1.675
11	0.598	10.001	599.982	0.718	0.123	0.112	0.076	0.189	1.584
12	0.645	11.000	659.978	0.721	0.126	0.115	0.079	0.193	1.670
13	0.653	12.001	720.037	0.723	0.130	0.116	0.081	0.197	1.654
14	0.687	13.001	780.093	0.726	0.133	0.118	0.083	0.202	1.703
15	0.712	14.001	840.033	0.728	0.136	0.120	0.086	0.205	1.734
16	0.735	15.000	899.980	0.729	0.138	0.121	0.087	0.208	1.771
17	0.740	16.000	960.047	0.730	0.142	0.121	0.090	0.211	1.753
18	0.777	16.999	1019.973	0.729	0.144	0.121	0.091	0.212	1.834
19	0.743	18.000	1079.916	0.728	0.147	0.120	0.093	0.213	1.743
20	0.788	19.000	1139.984	0.727	0.149	0.119	0.095	0.214	1.842
21	0.792	20.001	1200.090	0.726	0.151	0.118	0.096	0.215	1.846
22	0.785	20.999	1259.973	0.726	0.153	0.118	0.098	0.216	1.817
23	0.835	22.001	1320.026	0.725	0.155	0.118	0.099	0.217	1.927
24	0.787	23.001	1380.118	0.726	0.157	0.118	0.101	0.219	1.798
25	0.830	24.000	1440.004	0.725	0.159	0.118	0.102	0.220	1.890
26	0.775	25.000	1500.004	0.725	0.161	0.118	0.103	0.221	1.754
27	0.810	25.999	1559.979	0.724	0.163	0.117	0.105	0.222	1.827
28	0.799	27.001	1620.040	0.724	0.164	0.117	0.106	0.222	1.796
29	0.799	28.000	1679.938	0.723	0.165	0.116	0.106	0.222	1.797
30	0.808	29.000	1739.979	0.723	0.166	0.116	0.107	0.223	1.811
31	0.803	30.000	1799.919	0.722	0.167	0.115	0.108	0.223	1.800

Table 35: Data acquired from rectangular pushout test on sample 4 at initial Ntotal=0.30kN, test 4

Sample 4, Ntotal = 0.30kN, Test 4									
No.	Load F [kN]	Displ. [mm]	Time [s]	Voltage [V]		Normal force N [kN]			mu
				Cell 1	Cell 2	Cell 1	Cell 2	Total	
1	0.101	0.000	0.044	0.768	0.224	0.149	0.149	0.298	0.169
2	3.719	1.000	60.022	0.779	0.249	0.157	0.167	0.324	5.736
3	3.581	2.001	120.089	0.781	0.241	0.159	0.161	0.320	5.599
4	3.672	3.001	180.053	0.786	0.245	0.162	0.164	0.326	5.626
5	4.258	4.000	240.028	0.791	0.246	0.166	0.165	0.331	6.438
6	4.524	5.000	300.020	0.798	0.249	0.171	0.167	0.338	6.693
7	4.764	6.001	360.061	0.807	0.255	0.177	0.172	0.349	6.828
8	4.981	7.000	420.034	0.816	0.269	0.184	0.182	0.366	6.812
9	4.547	8.000	479.931	0.821	0.272	0.187	0.184	0.371	6.121
10	4.780	9.001	540.064	0.827	0.276	0.192	0.187	0.379	6.311
11	4.507	10.001	600.040	0.832	0.281	0.195	0.191	0.386	5.839
12	5.141	11.001	660.003	0.838	0.290	0.200	0.197	0.397	6.476
13	5.235	11.999	719.959	0.845	0.301	0.205	0.205	0.410	6.383
14	4.953	13.001	779.961	0.850	0.318	0.208	0.218	0.426	5.809
15	5.994	14.001	840.093	0.857	0.332	0.213	0.229	0.442	6.784
16	5.530	14.999	899.939	0.865	0.352	0.219	0.244	0.462	5.979
17	5.911	16.001	959.991	0.871	0.370	0.223	0.257	0.480	6.154
18	5.959	16.999	1019.857	0.878	0.386	0.228	0.269	0.497	5.990
19	6.182	18.000	1079.947	0.882	0.394	0.231	0.275	0.506	6.105
20	6.384	19.000	1139.972	0.899	0.408	0.243	0.286	0.529	6.034
21	6.110	20.000	1200.037	0.895	0.419	0.240	0.294	0.535	5.715
22	6.744	21.001	1260.051	0.903	0.429	0.246	0.302	0.548	6.154
23	5.802	22.000	1319.917	0.908	0.439	0.249	0.310	0.559	5.189
24	6.637	23.001	1380.039	0.911	0.437	0.251	0.308	0.560	5.929
25	6.761	24.000	1439.987	0.914	0.437	0.254	0.308	0.562	6.017
26	7.002	25.000	1500.025	0.917	0.442	0.256	0.312	0.568	6.166
27	6.497	26.000	1559.976	0.917	0.445	0.256	0.314	0.570	5.698
28	6.789	27.001	1620.015	0.917	0.449	0.256	0.317	0.573	5.922
29	6.855	28.001	1679.965	0.918	0.457	0.256	0.324	0.580	5.909
30	6.617	29.000	1739.976	0.915	0.470	0.254	0.334	0.588	5.627
31	6.273	29.986	1799.148	0.915	0.477	0.254	0.339	0.593	5.286

Table 36: Data acquired from rectangular pushout test on sample 5 at initial Ntotal=0.20kN, test 2

Sample 5, Ntotal = 0.20kN, Test 2									
No.	Load F [kN]	Displ. [mm]	Time [s]	Voltage [V]		Normal force N [kN]			mu
				Cell 1	Cell 2	Cell 1	Cell 2	Total	
1	0.099	0.001	0.041	0.712	0.173	0.108	0.112	0.220	0.225
2	1.276	1.000	59.969	0.724	0.227	0.117	0.151	0.268	2.382
3	1.333	2.001	120.044	0.733	0.287	0.123	0.195	0.319	2.092
4	1.393	2.999	179.944	0.735	0.284	0.125	0.193	0.318	2.192
5	1.442	4.000	240.003	0.736	0.283	0.126	0.192	0.318	2.269
6	1.485	5.001	299.960	0.738	0.284	0.127	0.193	0.320	2.320
7	1.534	6.000	359.970	0.740	0.284	0.129	0.193	0.321	2.386
8	1.621	7.001	420.047	0.742	0.285	0.130	0.194	0.324	2.504
9	1.658	8.001	480.049	0.746	0.288	0.133	0.196	0.329	2.521
10	1.782	9.000	539.997	0.748	0.293	0.134	0.200	0.334	2.668
11	1.846	10.000	599.975	0.751	0.298	0.137	0.203	0.340	2.715
12	1.910	11.001	659.975	0.754	0.307	0.139	0.210	0.349	2.738
13	1.960	12.001	720.049	0.757	0.316	0.141	0.217	0.358	2.740
14	1.965	13.000	780.017	0.759	0.326	0.142	0.224	0.367	2.680
15	2.004	14.001	840.049	0.762	0.333	0.145	0.229	0.374	2.679
16	2.026	15.000	900.036	0.765	0.342	0.147	0.236	0.383	2.645
17	2.089	16.001	960.051	0.767	0.352	0.148	0.244	0.392	2.665
18	2.119	17.001	1019.956	0.770	0.361	0.151	0.250	0.401	2.643
19	2.124	18.001	1080.058	0.772	0.367	0.152	0.255	0.407	2.610
20	2.153	19.000	1139.994	0.772	0.372	0.152	0.259	0.411	2.622
21	2.171	20.000	1199.950	0.774	0.375	0.153	0.261	0.414	2.620
22	2.181	21.001	1260.034	0.777	0.379	0.156	0.264	0.420	2.599
23	2.227	22.000	1320.010	0.777	0.385	0.156	0.269	0.424	2.625
24	2.192	23.000	1380.049	0.779	0.390	0.157	0.272	0.429	2.553
25	2.129	24.001	1439.972	0.782	0.411	0.159	0.288	0.448	2.379
26	2.003	25.000	1499.969	0.782	0.412	0.159	0.289	0.448	2.234
27	2.025	26.001	1559.978	0.781	0.418	0.159	0.294	0.452	2.239
28	2.010	27.001	1619.990	0.779	0.431	0.157	0.304	0.461	2.182
29	1.997	28.001	1680.055	0.778	0.431	0.156	0.304	0.460	2.171
30	2.039	28.999	1739.955	0.778	0.432	0.156	0.304	0.461	2.213
31	2.072	30.000	1799.942	0.778	0.433	0.156	0.305	0.461	2.245

Table 37: Data acquired from rectangular pushout test on sample 5 at initial Ntotal=0.10kN, test 3

Sample 5, Ntotal = 0.10kN, Test 3									
No.	Load F [kN]	Displ. [mm]	Time [s]	Voltage [V]		Normal force N [kN]			mu
				Cell 1	Cell 2	Cell 1	Cell 2	Total	
1	0.098	0.001	0.065	0.637	0.089	0.052	0.052	0.104	0.471
2	0.617	0.999	59.963	0.669	0.097	0.076	0.058	0.134	2.304
3	0.636	2.001	119.971	0.683	0.102	0.086	0.062	0.148	2.150
4	0.629	3.001	180.037	0.694	0.106	0.095	0.064	0.159	1.979
5	0.638	4.000	239.991	0.693	0.108	0.094	0.066	0.160	1.999
6	0.654	5.001	300.056	0.693	0.108	0.094	0.066	0.160	2.049
7	0.696	6.000	359.957	0.693	0.110	0.094	0.067	0.161	2.161
8	0.722	7.000	419.993	0.695	0.112	0.095	0.069	0.164	2.202
9	0.742	8.000	479.936	0.699	0.116	0.098	0.071	0.170	2.186
10	0.786	9.001	540.057	0.701	0.119	0.100	0.074	0.173	2.267
11	0.804	10.000	599.995	0.704	0.122	0.102	0.076	0.178	2.262
12	0.831	11.000	660.011	0.709	0.126	0.106	0.079	0.184	2.255
13	0.867	12.000	720.006	0.715	0.131	0.110	0.082	0.192	2.255
14	1.033	13.001	779.941	0.769	0.180	0.150	0.117	0.267	1.936
15	0.721	14.001	840.062	0.750	0.136	0.136	0.086	0.222	1.627
16	0.752	15.001	900.049	0.751	0.137	0.137	0.086	0.223	1.686
17	0.760	16.000	959.977	0.753	0.137	0.138	0.086	0.224	1.693
18	0.796	17.001	1020.029	0.755	0.134	0.140	0.084	0.224	1.779
19	0.826	18.001	1079.959	0.757	0.134	0.141	0.084	0.225	1.834
20	0.861	19.001	1140.090	0.759	0.134	0.142	0.084	0.227	1.899
21	0.906	19.999	1199.953	0.761	0.134	0.144	0.084	0.228	1.986
22	0.943	21.001	1259.994	0.763	0.134	0.145	0.084	0.230	2.054
23	0.963	22.001	1320.055	0.764	0.134	0.146	0.084	0.230	2.091
24	0.976	23.000	1380.032	0.765	0.134	0.147	0.084	0.231	2.112
25	0.988	24.001	1439.980	0.766	0.135	0.148	0.085	0.232	2.125
26	0.999	25.001	1500.030	0.768	0.135	0.149	0.085	0.234	2.135
27	1.014	26.000	1559.932	0.771	0.136	0.151	0.086	0.237	2.141
28	1.024	27.000	1619.992	0.773	0.136	0.153	0.086	0.238	2.149
29	1.021	28.000	1680.016	0.775	0.137	0.154	0.086	0.240	2.123
30	1.030	29.001	1740.047	0.778	0.138	0.156	0.087	0.243	2.116
31	1.052	29.999	1799.917	0.781	0.138	0.159	0.087	0.246	2.142

Table 38: Data acquired from rectangular pushout test on sample 5 at initial Ntotal=0.30kN, test 4

Sample 5, Ntotal = 0.30kN, Test 4									
No.	Load F [kN]	Displ. [mm]	Time [s]	Voltage [V]		Normal force N [kN]			mu
				Cell 1	Cell 2	Cell 1	Cell 2	Total	
1	0.102	0.000	0.044	0.765	0.207	0.147	0.137	0.283	0.180
2	1.977	1.000	60.008	0.774	0.210	0.153	0.139	0.292	3.384
3	2.145	2.001	120.054	0.781	0.222	0.159	0.147	0.306	3.506
4	2.232	3.000	179.934	0.780	0.229	0.158	0.153	0.310	3.596
5	2.295	4.000	240.014	0.780	0.233	0.158	0.155	0.313	3.663
6	2.363	5.001	300.134	0.782	0.236	0.159	0.158	0.317	3.729
7	2.472	6.001	360.067	0.785	0.246	0.161	0.165	0.326	3.787
8	2.567	7.001	419.974	0.790	0.254	0.165	0.171	0.336	3.822
9	2.656	8.000	479.976	0.796	0.261	0.169	0.176	0.345	3.846
10	2.737	9.001	540.059	0.802	0.269	0.174	0.182	0.356	3.849
11	2.839	10.001	600.058	0.809	0.278	0.179	0.188	0.367	3.866
12	2.911	11.001	660.058	0.816	0.284	0.184	0.193	0.377	3.864
13	2.980	12.001	720.019	0.823	0.288	0.189	0.196	0.385	3.873
14	3.073	13.001	780.043	0.832	0.293	0.195	0.200	0.395	3.891
15	3.169	14.001	840.059	0.841	0.298	0.202	0.203	0.405	3.912
16	3.243	15.001	900.063	0.850	0.299	0.208	0.204	0.412	3.934
17	3.321	16.001	960.061	0.859	0.301	0.215	0.205	0.420	3.953
18	3.404	17.000	1020.008	0.868	0.305	0.221	0.208	0.429	3.963
19	3.466	18.001	1080.061	0.875	0.310	0.226	0.212	0.438	3.955
20	3.530	19.001	1140.064	0.880	0.310	0.230	0.212	0.442	3.996
21	3.508	20.000	1199.945	0.886	0.309	0.234	0.211	0.445	3.940
22	3.487	21.001	1260.059	0.891	0.307	0.237	0.210	0.447	3.898
23	3.445	22.001	1320.018	0.896	0.308	0.241	0.211	0.452	3.815
24	3.544	23.001	1379.994	0.900	0.311	0.244	0.213	0.457	3.881
25	3.561	24.000	1439.995	0.903	0.315	0.246	0.216	0.462	3.856
26	3.431	25.001	1500.088	0.906	0.315	0.248	0.216	0.464	3.698
27	3.589	26.000	1559.931	0.910	0.314	0.251	0.215	0.466	3.851
28	3.142	27.001	1620.015	0.913	0.315	0.253	0.216	0.469	3.351
29	3.408	28.001	1680.000	0.915	0.319	0.254	0.219	0.473	3.601
30	3.391	29.000	1739.934	0.920	0.320	0.258	0.220	0.477	3.551
31	3.308	30.000	1799.940	0.921	0.323	0.259	0.222	0.480	3.443

Table 39: Data acquired from rectangular pushout test on sample 6 at initial Ntotal=0.20kN, test 1

Sample 6, Ntotal = 0.20kN, Test 1									
No.	Load F [kN]	Displ. [mm]	Time [s]	Voltage [V]		Normal force N [kN]			mu
				Cell 1	Cell 2	Cell 1	Cell 2	Total	
1	0.104	0.000	0.074	0.700	0.143	0.099	0.091	0.190	0.274
2	1.941	1.000	60.013	0.725	0.180	0.118	0.117	0.235	4.137
3	2.094	2.000	120.019	0.730	0.173	0.121	0.112	0.233	4.488
4	2.091	3.001	180.006	0.738	0.207	0.127	0.137	0.264	3.965
5	2.118	4.001	240.038	0.736	0.205	0.126	0.135	0.261	4.061
6	2.192	5.001	300.012	0.737	0.204	0.126	0.134	0.261	4.203
7	2.298	6.000	360.002	0.739	0.205	0.128	0.135	0.263	4.370
8	2.479	7.000	419.995	0.741	0.210	0.129	0.139	0.268	4.624
9	2.583	8.000	479.951	0.742	0.217	0.130	0.144	0.274	4.716
10	2.709	9.000	540.014	0.744	0.225	0.132	0.150	0.281	4.818
11	2.801	10.000	599.929	0.745	0.233	0.132	0.155	0.288	4.868
12	2.906	11.001	660.048	0.747	0.243	0.134	0.163	0.296	4.901
13	2.972	12.000	719.982	0.746	0.250	0.133	0.168	0.301	4.939
14	3.010	13.001	780.058	0.746	0.258	0.133	0.174	0.307	4.907
15	3.012	14.000	839.936	0.745	0.262	0.132	0.177	0.309	4.875
16	2.967	15.001	900.055	0.743	0.261	0.131	0.176	0.307	4.836
17	2.962	16.000	960.048	0.740	0.266	0.129	0.180	0.308	4.805
18	2.976	17.000	1020.017	0.740	0.270	0.129	0.183	0.311	4.782
19	2.951	18.000	1080.002	0.739	0.273	0.128	0.185	0.313	4.720
20	2.946	19.000	1140.040	0.739	0.276	0.128	0.187	0.315	4.679
21	2.917	20.000	1199.954	0.738	0.276	0.127	0.187	0.314	4.643
22	2.934	21.000	1260.011	0.738	0.284	0.127	0.193	0.320	4.584
23	2.900	22.000	1320.019	0.739	0.293	0.128	0.200	0.327	4.429
24	2.968	23.001	1380.063	0.739	0.294	0.128	0.200	0.328	4.522
25	2.978	24.000	1440.008	0.741	0.297	0.129	0.203	0.332	4.487
26	3.013	25.001	1500.011	0.742	0.299	0.130	0.204	0.334	4.510
27	3.048	26.000	1560.032	0.742	0.302	0.130	0.206	0.336	4.532
28	3.102	27.000	1619.982	0.744	0.307	0.132	0.210	0.341	4.542
29	3.076	28.001	1680.020	0.743	0.308	0.131	0.211	0.341	4.504
30	2.932	29.001	1740.079	0.743	0.312	0.131	0.214	0.344	4.256
31	2.885	30.000	1800.061	0.741	0.309	0.129	0.211	0.341	4.233

Table 40: Data acquired from rectangular pushout test on sample 6 at initial Ntotal=0.20kN, test 2

Sample 6, Ntotal = 0.20kN, Test 2									
No.	Load F [kN]	Displ. [mm]	Time [s]	Voltage [V]		Normal force N [kN]			mu
				Cell 1	Cell 2	Cell 1	Cell 2	Total	
1	0.094	0.000	0.046	0.698	0.150	0.098	0.096	0.193	0.243
2	1.090	0.999	59.968	0.726	0.142	0.118	0.090	0.208	2.618
3	1.129	2.000	119.980	0.738	0.148	0.127	0.094	0.221	2.551
4	1.176	3.000	179.998	0.743	0.145	0.131	0.092	0.223	2.639
5	1.244	4.001	240.021	0.755	0.151	0.140	0.096	0.236	2.637
6	1.312	5.001	300.003	0.765	0.154	0.147	0.098	0.245	2.674
7	1.389	6.001	360.028	0.772	0.158	0.152	0.101	0.253	2.742
8	1.468	7.001	420.103	0.779	0.161	0.157	0.103	0.260	2.818
9	1.535	8.001	480.087	0.786	0.163	0.162	0.105	0.267	2.875
10	1.576	9.001	540.090	0.792	0.163	0.166	0.105	0.271	2.904
11	1.639	10.000	600.011	0.797	0.165	0.170	0.106	0.276	2.965
12	1.692	11.000	659.985	0.803	0.167	0.174	0.108	0.282	2.998
13	1.740	12.001	720.030	0.808	0.169	0.178	0.109	0.287	3.029
14	1.787	13.001	780.050	0.814	0.170	0.182	0.110	0.292	3.057
15	1.809	14.001	840.038	0.819	0.173	0.186	0.112	0.298	3.035
16	1.884	15.001	900.098	0.823	0.175	0.189	0.113	0.302	3.116
17	1.924	16.001	960.046	0.828	0.177	0.192	0.115	0.307	3.130
18	1.968	17.001	1020.087	0.832	0.179	0.195	0.116	0.312	3.158
19	2.035	18.000	1080.029	0.836	0.180	0.198	0.117	0.315	3.228
20	2.062	19.001	1140.095	0.839	0.181	0.200	0.118	0.318	3.241
21	2.117	19.999	1199.992	0.842	0.182	0.202	0.119	0.321	3.298
22	2.160	21.000	1259.918	0.843	0.184	0.203	0.120	0.323	3.343
23	2.209	22.001	1320.041	0.845	0.185	0.205	0.121	0.325	3.396
24	2.179	23.001	1380.038	0.847	0.187	0.206	0.122	0.328	3.320
25	2.160	24.000	1439.924	0.849	0.189	0.207	0.124	0.331	3.263
26	2.248	25.001	1499.989	0.849	0.190	0.207	0.124	0.332	3.388
27	2.250	25.999	1559.938	0.850	0.192	0.208	0.126	0.334	3.370
28	2.178	27.001	1620.051	0.852	0.194	0.210	0.127	0.337	3.234
29	2.134	28.000	1680.027	0.854	0.199	0.211	0.131	0.342	3.122
30	2.207	29.000	1739.983	0.855	0.200	0.212	0.131	0.343	3.215
31	2.273	29.999	1799.923	0.855	0.200	0.212	0.131	0.343	3.311

Table 41: Data acquired from rectangular pushout test on sample 6 at initial Ntotal=0.10kN, test 3

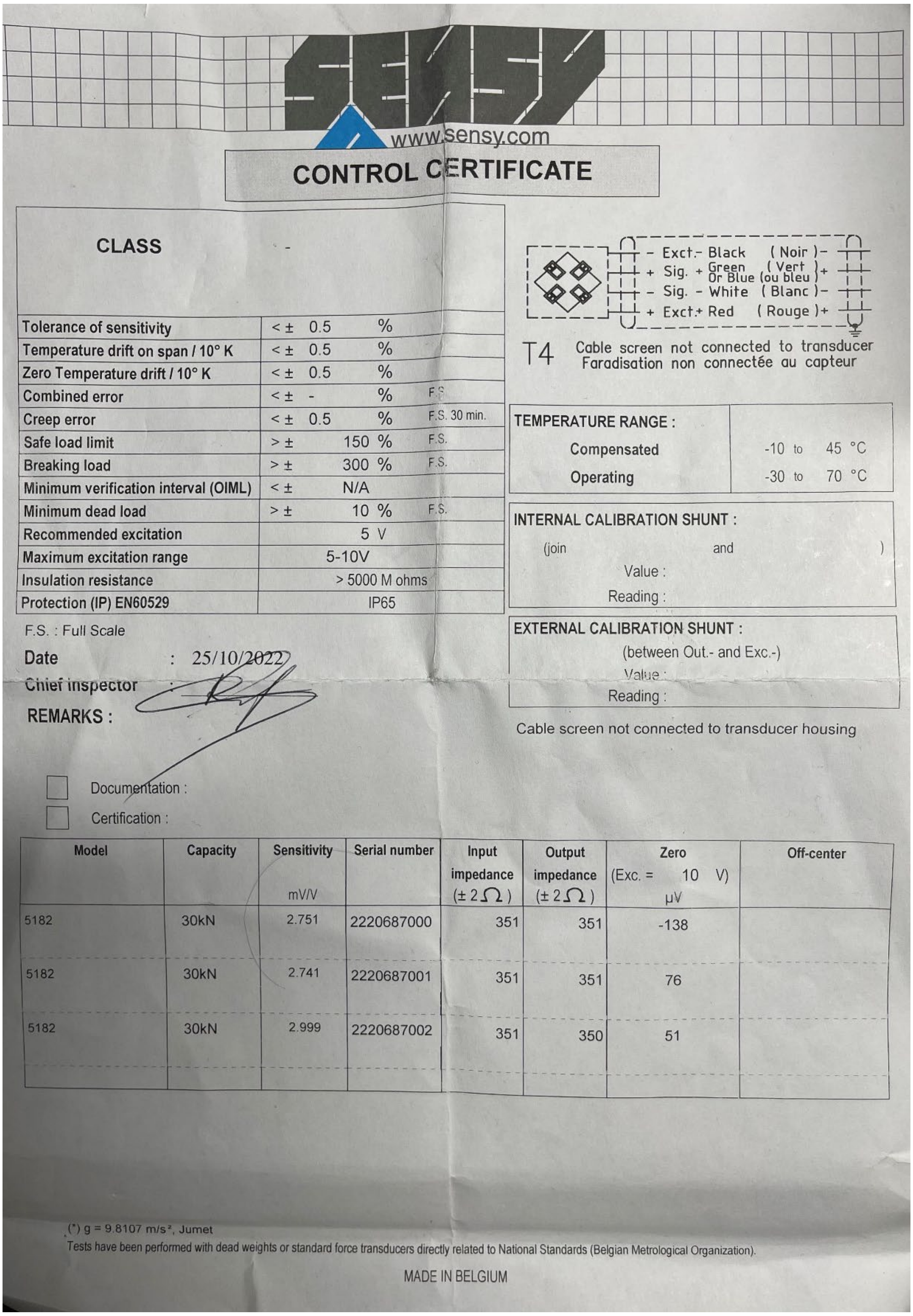
Sample 6, Ntotal = 0.10kN, Test 3									
No.	Load F [kN]	Displ. [mm]	Time [s]	Voltage [V]		Normal force N [kN]			mu
				Cell 1	Cell 2	Cell 1	Cell 2	Total	
1	0.099	0.000	0.085	0.635	0.082	0.050	0.047	0.098	0.507
2	1.143	0.999	59.930	0.623	0.100	0.041	0.060	0.101	5.647
3	1.150	2.000	120.023	0.625	0.108	0.043	0.066	0.108	5.306
4	1.167	3.000	179.966	0.625	0.111	0.043	0.068	0.110	5.281
5	1.150	4.001	240.065	0.625	0.116	0.043	0.071	0.114	5.043
6	1.179	5.000	299.932	0.626	0.121	0.043	0.075	0.118	4.982
7	1.229	6.000	360.012	0.628	0.123	0.045	0.076	0.121	5.067
8	1.252	7.000	420.009	0.629	0.126	0.046	0.079	0.124	5.042
9	1.239	8.000	480.029	0.631	0.125	0.047	0.078	0.125	4.957
10	1.262	9.000	540.027	0.631	0.125	0.047	0.078	0.125	5.049
11	1.275	10.000	600.002	0.632	0.125	0.048	0.078	0.126	5.070
12	1.273	11.000	660.023	0.632	0.127	0.048	0.079	0.127	5.006
13	1.304	12.001	719.987	0.631	0.128	0.047	0.080	0.127	5.130
14	1.294	13.001	780.048	0.632	0.135	0.048	0.085	0.133	4.871
15	1.289	13.999	839.967	0.630	0.136	0.046	0.086	0.132	4.882
16	1.295	14.999	899.931	0.629	0.137	0.046	0.086	0.132	4.907
17	1.312	16.000	959.911	0.628	0.139	0.045	0.088	0.133	4.946
18	1.289	17.001	1020.064	0.628	0.144	0.045	0.091	0.136	4.733
19	1.317	18.001	1079.988	0.627	0.144	0.044	0.091	0.135	4.863
20	1.314	19.000	1140.002	0.627	0.149	0.044	0.095	0.139	4.727
21	1.325	20.001	1200.057	0.627	0.153	0.044	0.098	0.142	4.671
22	1.312	21.001	1260.052	0.625	0.153	0.043	0.098	0.140	4.675
23	1.350	22.001	1320.106	0.624	0.158	0.042	0.101	0.143	4.716
24	1.333	23.000	1379.983	0.624	0.165	0.042	0.106	0.148	4.499
25	1.321	24.001	1440.043	0.624	0.173	0.042	0.112	0.154	4.293
26	1.322	25.000	1499.973	0.623	0.174	0.041	0.113	0.154	4.297
27	1.358	26.000	1560.012	0.622	0.179	0.040	0.116	0.157	4.334
28	1.338	27.000	1619.998	0.623	0.189	0.041	0.124	0.165	4.064
29	1.345	28.000	1679.970	0.622	0.188	0.040	0.123	0.163	4.122
30	1.426	29.001	1740.038	0.626	0.214	0.043	0.142	0.185	3.854
31	1.119	29.999	1800.004	0.622	0.211	0.040	0.139	0.180	3.112

Table 42: Data acquired from rectangular pushout test on sample 6 at initial Ntotal=0.30kN, test 4

Sample 6, Ntotal = 0.30kN, Test 4									
No.	Load F [kN]	Displ. [mm]	Time [s]	Voltage [V]		Normal force N [kN]			mu
				Cell 1	Cell 2	Cell 1	Cell 2	Total	
1	0.099	0.001	0.061	0.774	0.235	0.153	0.157	0.310	0.160
2	3.325	0.999	59.919	0.789	0.246	0.164	0.165	0.329	5.049
3	3.215	2.001	120.031	0.800	0.266	0.172	0.180	0.352	4.568
4	3.314	3.001	179.975	0.810	0.294	0.179	0.200	0.380	4.363
5	3.225	4.000	239.987	0.814	0.291	0.182	0.198	0.380	4.239
6	3.582	5.001	300.043	0.817	0.292	0.185	0.199	0.383	4.672
7	3.719	5.999	359.941	0.823	0.296	0.189	0.202	0.391	4.761
8	3.929	7.000	420.013	0.832	0.310	0.195	0.212	0.407	4.821
9	4.110	8.000	479.935	0.842	0.319	0.202	0.219	0.421	4.877
10	4.076	9.000	540.004	0.852	0.330	0.210	0.227	0.437	4.667
11	4.294	10.001	600.054	0.862	0.338	0.217	0.233	0.450	4.773
12	4.536	11.001	660.063	0.872	0.345	0.224	0.238	0.462	4.907
13	4.535	12.000	719.998	0.885	0.354	0.233	0.245	0.478	4.742
14	4.767	13.000	780.036	0.895	0.357	0.240	0.247	0.488	4.889
15	4.804	14.000	839.985	0.907	0.364	0.249	0.253	0.501	4.792
16	5.004	15.001	899.988	0.918	0.368	0.256	0.256	0.512	4.886
17	5.196	16.001	960.057	0.929	0.372	0.264	0.259	0.523	4.969
18	5.053	17.000	1019.941	0.939	0.377	0.271	0.262	0.534	4.734
19	5.215	18.000	1079.950	0.949	0.379	0.278	0.264	0.542	4.809
20	5.126	19.001	1139.986	0.957	0.382	0.284	0.266	0.550	4.659
21	5.305	20.001	1199.969	0.963	0.379	0.288	0.264	0.552	4.805
22	5.412	21.000	1259.978	0.968	0.377	0.292	0.262	0.554	4.884
23	4.994	22.000	1320.029	0.979	0.380	0.299	0.265	0.564	4.427
24	5.301	23.000	1379.935	0.983	0.377	0.302	0.262	0.565	4.695
25	5.197	24.000	1440.002	0.989	0.377	0.306	0.262	0.569	4.569
26	5.479	25.000	1499.894	0.991	0.371	0.308	0.258	0.566	4.843
27	5.910	26.001	1560.061	0.992	0.364	0.308	0.253	0.561	5.267
28	5.682	27.000	1619.937	1.000	0.360	0.314	0.250	0.564	5.041
29	5.388	28.000	1679.953	1.003	0.355	0.316	0.246	0.562	4.794
30	5.693	29.000	1739.967	1.004	0.350	0.317	0.242	0.559	5.093
31	5.760	30.000	1799.987	1.007	0.343	0.319	0.237	0.556	5.182

Appendix C

Figure 139: Control certificate for compression washer load cells for Sensy



www.sensy.com

CONTROL CERTIFICATE

CLASS -

Tolerance of sensitivity	< ± 0.5 %	
Temperature drift on span / 10° K	< ± 0.5 %	
Zero Temperature drift / 10° K	< ± 0.5 %	
Combined error	< ± - %	F.S.
Creep error	< ± 0.5 %	F.S. 30 min.
Safe load limit	> ± 150 %	F.S.
Breaking load	> ± 300 %	F.S.
Minimum verification interval (OIML)	< ± N/A	
Minimum dead load	> ± 10 %	F.S.
Recommended excitation	5 V	
Maximum excitation range	5-10V	
Insulation resistance	> 5000 M ohms	
Protection (IP) EN60529	IP65	

F.S. : Full Scale

Date : 25/10/2022

Chief inspector :

REMARKS :

- Exct.- Black (Noir)-
+ Sig. + Green Or Blue (Vert (ou bleu))+
- Sig. - White (Blanc)-
+ Exct.+ Red (Rouge)+

T4 Cable screen not connected to transducer
Faradisation non connectée au capteur

TEMPERATURE RANGE :

Compensated	-10 to 45 °C
Operating	-30 to 70 °C

INTERNAL CALIBRATION SHUNT :
(join and)
Value :
Reading :

EXTERNAL CALIBRATION SHUNT :
(between Out.- and Exc.-)
Value :
Reading :

Cable screen not connected to transducer housing

Documentation :

Certification :

Model	Capacity	Sensitivity mV/V	Serial number	Input impedance (± 2 Ω)	Output impedance (± 2 Ω)	Zero (Exc. = 10 V) µV	Off-center
5182	30kN	2.751	2220687000	351	351	-138	
5182	30kN	2.741	2220687001	351	351	76	
5182	30kN	2.999	2220687002	351	350	51	

(*) g = 9.8107 m/s², Jumet

Tests have been performed with dead weights or standard force transducers directly related to National Standards (Belgian Metrological Organization).

MADE IN BELGIUM