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Summary

Slipforming is a construction method that has been used in many years for production of concrete structures and it is mainly suited for tall structures such as towers, bridge columns, silos, and offshore platforms with simple geometry. However, unlike fixed formwork, the friction occurs between the formwork and the concrete surface during the process of slipforming, can cause lifting crack and other surface damage in the concrete if the friction is high.

The objective is to determine how the pore water pressure and frictional force between the slipform panel and environmentally friendly concrete develop, when the amount of clinker in the cement replaced by amount of fly ash. This process can help to limit CO2 emission into the atmosphere and minimizes environmental pollution. In addition, how the surface damage affected by the change also studied during the process of slipform.

The research comprises of two main parts: A review of relevant literature study and a laboratory testing program.

In the literature part, a theoretical study to understand the phenomena that affects the pore water pressure and the friction at the interface between the building-up concrete and the sliding panel is briefly described. In addition, the basic theory and principles of the slip form rig and properties of a fresh and hardened concrete is briefly explained.

A practical experimental test program was carried out in the concrete laboratory at the University of Stavanger. A total of 7-8 concrete mixes was planned to be tested in the sliding rig. Unfortunately, only 4 concrete mixes given from E39 Sulafjorden were carried out due to the corona virus lock-down of the laboratory at University of Stavanger.

In the experiment a cement with a combination of different amount of clinker and fly ash used to investigate how the friction and porewater pressure affected in slipforming process. Four mixes, two with 0.35 w/b ratio (mix-3 and mix-5) and the other two with 0.30 w/b ratio (mix-4 and mix-6) was used. Portland-fly ash (Anleggsement FA) that contains 85% clinker and 15% fly ash was used to prepare the concrete mix-3 and mix-4 and in the other two mixes a 20% clinker was replaced by fly ash.

The data from the experiments plotted in a graph to compare the evolution of different parameters that affect the slipforming process between the concrete mixes with same w/b ratio and different amount of clinker and fly ash. the focus was done on the trend in decreasing rate of the pore water pressure, which is the main objective, and found to be satisfactory in most cases according to the theory study. But the properties of fresh concrete mixes showed a reasonable difference from the original data obtained from E39 Sulafjorden. For instance, the data for slump measurements exhibits a relevant difference from that of given data. As a result, the workability of the concrete was not as intended (self-compacted concrete). A vibrator was used during casting of the concrete in the slip form rig.

The rate of decreasing of pore water pressure is higher in the concrete mix with normal Anleggsement FA and lower rate of decreasing of pore water pressure in the concrete mix with 20% clinker replacement with fly ash. The lifting force is maximum when the pore water pressure is at its minimum value. The pore water pressure decreases at the early stage of casting and starts to increase after a while and decreases until it comes to rise sharply at a constant rate then disappears at the final stage. These observations can be related to the lecture study that the early stage decreasing is because of the settlement in the fresh concrete. And after a while (during the elastic phase), the pore water pressure starts to decrease faster as an effect of the chemical shrinkage that occurs because of the cement reaction. And the final disappearance can be related to the break-through process.

The development of the temperature and surface damage also carefully studied. From the result it is clearly shown that the rate of the development of temperature is higher in the concrete mix with Anleggsement FA and the higher w/b ratio has higher rate of development of temperature.

According to the lecture study, the risk for surface damage is higher in case of high friction. But in this experiment, there was not any surface damage seen. The surface of the hardened concrete was smooth and sound.

Table of Contents

List of Figures

List of Tables

1. Introduction

1.1. Background

Slipforming is a type of concrete casting usually applied in the production of rather high, vertical structures such as Silos, towers, chimneys, shafts for structures etc (1). Slipforming is normally a continuous working operation (the process should not be halted after it has been initiated), which always require a well-planned supply of materials and personnel present. The active principle of the slipforming process consists of a quasi-continuous perpendicular lifting process of the formwork construction while all the usual steps executed concurrently: Forming, reinforcing, placing of concrete and after treating. The formwork grows upwards with the structure up to several meters a day. In general, the works are carried out in 24 hours shift rotations, but slipforming only during the day is possible, as well (2).

Slipforming is a rather complicated operation compared to other construction techniques. The requirements to the materials, personnel and the execution of the work are therefore accordingly higher. During slipforming, unlike fixed formwork, sometimes occurs surface damages such as lifting cracks and vertical surface damages. This is because of the high friction between the concrete and slipforming panel. From a concrete technology point of view, there are several challenges in slipforming (3).

1.2. Principles of a vertical slipform

Vertical slipforms are composed of three basic sections: yokes, vertical walls, and sheathing. (see Figure 1).

The yokes are inverted U's consisting of two legs and a cross beam. The legs are attached to the wales and carry the vertical loads in tension, and the lateral loads as cantilever beams. The cross arm of the yoke must be designed as a simple beam supported at the centre by the jack and subject to the moments from both the vertical and lateral leg loads. Although yokes are normally of steel, they can be constructed of wood or other material. They should also be designed with enough clearance above the forms to allow horizontal reinforcement steel and embedded items (block outs, insert material) to be installed in a correct fashion prior to being submerged in the concrete.

Vertical wales are mainly used to support and hold the sheathing, working platform and suspended scaffolding, and transmit the lifting forces from the yokes to the form system.

The sheathing makes up the sides or walls of the forms and is the portion of the formwork which contains and shapes the concrete. Since slip-forms are subjected to the hydrostatic pressure of the plastic concrete, the sheathing must support this lateral pressure with beam action between the wales, and as a cantilever at the bottom of the form (4).

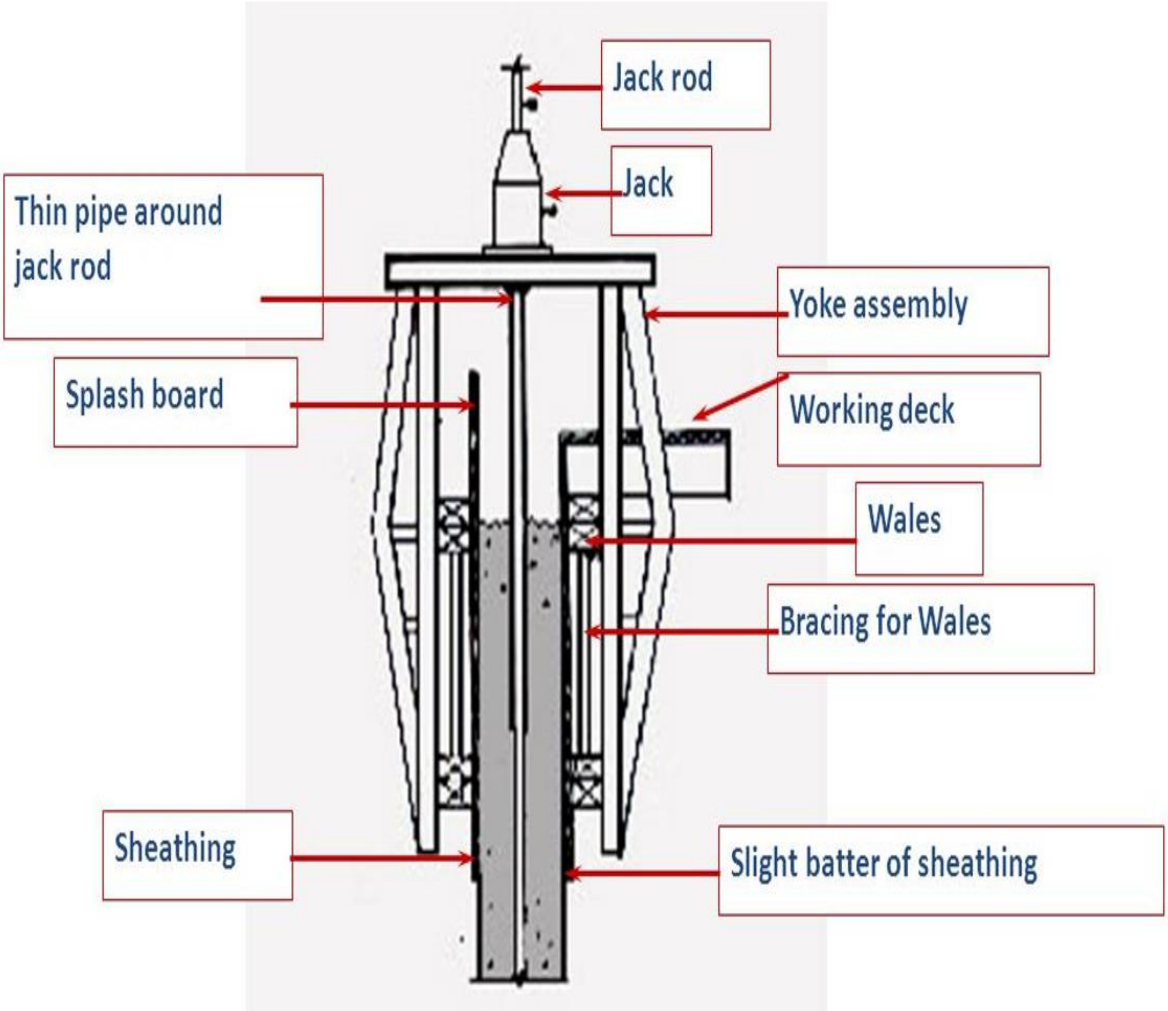


Figure 1 Principles of slipforming (4)

1.3. Objectives

The objective of this thesis is to examine (study) how pore water pressure can affect the frictional force occurring between the surface of slipform panel and environmentally friendly concrete structures.

The objective is to determine how the pore water pressure and frictional force between the slipform panel and concrete affected when the amount of clinker in concrete replaced by fly ash keeping all the other properties of the concrete and w/b ratio unchanged. In addition, to determine the development of temperature and the surface damage effects in the concrete mixes.

1.4. Scope of work

This thesis consists of two main sections, the first section is a literature study on experience made with slipforming with a focus on effects of pore water pressure and frictional force between the slip panel and concrete, and properties of fresh concrete.

The second section is a laboratory program which includes practical slip formwork for 4 given proportions of concrete mix. Environmentally friendly concrete mix of different w/b ratio and amount of clinker and fly ash were used. A range of tests were performed to determine how the effect of pore water pressure and friction in each mix design during vertical slipforming process.

2. Literature review

2.1. Slipforming

2.1.1. Description

Slipforming is a construction method for concrete and it is especially suited for tall constructions with simple geometry.

Concrete slipform construction, which is sometimes referred to as sliding form construction, is a type of extrusion process. Plastic concrete is placed or pumped into moving forms which shape and hold the concrete until it is self-supporting. Vertical slipform techniques as the term implies, is associated with the vertical construction of such structures as water tanks, silos, and multi-storied buildings. Horizontal Slipform construction as described herein will include the techniques used in the construction of such structures as canal linings, concrete pipe, highway pavement, and tunnel inverts. (4)

With vertical slipforming one utilizes the concrete setting time to create a homogeneous layer. This is achieved by pouring concrete layer by layer into a form, which is lifted upwards gradually by a hydraulic jacking system. This allows the concrete layers to merge into each other and create good adhesion and one gets a homogeneous layer.

2.1.2. Vertical slipforming

In general, vertical slipform construction is the uninterrupted vertical moulding of concrete walls through the use of a 1.1-1.3 metre form which is lifted in small (25-30 cm) but continual increments while fresh concrete and reinforcing steel are placed in the top of the open form. Thus, vertical slipforming is an extrusion process where the material is stationary, and the form moves upward. Normally the setting time of concrete is 2-3 hours. Using this typical setting time and with slipforms 4 feet deep, a possible form speed of 16-24 inches per hour can be achieved. The actual median form speed however, depends on such factors as the concreting temperatures, the concrete admixtures used, the grind of the cement, the water-cement ratio, the percent of fines in the concrete aggregate, the symmetry of the structure being constructed, required variations in wall thickness, the amount and complexity of rebar placement, the jack spacing, the number of block-outs required, and the depth of the forms.

Because slipforming is an extrusion process, nothing can be cast that is not within the confines of the inner and outer sheathing of the moving forms. This means that beams, slabs, corbels, or other horizontal elements cannot be cast simultaneously with the walls but must be placed later (4).

2.1.3. Advantages of slipforming

The main advantage of slipform equipment is the considerable reduction in construction time. For vertical structures like an RCC chimney, an average progress of 3 to 4m per day can easily be achieved with slip form equipment. Such a rate of progress would be impossible to achieve with conventional form work or jump formwork equipment. A height of as much as 8m can be achieved on a day if weather and other factors permit, though it may not be recommended to achieve such high progress every day.

Another big advantage is that the construction joints get eliminated as the slipform equipment works on a round-the clock basis only in exceptional cases are interruptions planned for extraction of jack rods. When conventional forms or jump-forms are used, construction joints occur after every lift 0f 1.2 to 1.5m but with slip forms construction joints may be planned after every 50m (5).

Another advantages of slip form (3):

- Casting of thin concrete layers and with a low lifting rate provides favourable conditions for vibrating the concrete.
- No need for spacers in the nominal cover.
- When the construction process is planned carefully it is possible to achieve a high production rate.
- The progress is relatively independent of weather conditions.
- There is good visual control of the placement and compaction of the concrete.
- The concrete that is left exposed when the form is lifted allows it to be finished.

On the contrary the following disadvantages can be obtained using a slipform (3):

- The nominal cover is constantly affected by the lifting of the form from it is poured until it hardens. This can give surface damages.
- Lump formation and materials sticking to the panel will give vertical damages.
- Vibrating on the reinforcement could give cavities along the reinforcement and poor adhesion.
- There is a time pressure on the steel fixers on placing and tying the reinforcements.
- The work must continue regardless of whether the weather gets bad.
- With slipforming it is required a greater alertness and control than other methods.
- Unforeseen delay in supply of concrete could possible stop the slipform.

2.1.4. Slipforming rate

A slipform operation is a continuous working process where the slipform is kept close to full of concrete while it is lifted stepwise. The concrete is placed in 100 to 250 mm thick layers whenever the freeboard height is sufficient. Usually the slipform rate is adjusted so that the initial set in the concrete occur between 200 to 400 mm above the bottom of the panel. Depending on the inclination of the panel, the concrete will detach the slipform panel above the hardening front where the concrete skeleton is rigid enough to resist backsliding (3).

The slipform rate is planned based on the concrete structure complexity, manning, the skills of the work force and limitation in the material supply. The setting time of the concrete is adjusted to fit the planned slipform rate. The setting time of the concrete depends on the temperature, concrete composition, and the properties of the cement. The concrete setting time can also be adjusted by using retarding or accelerating admixtures. The relation between the concrete setting time and the slipform rate can be calculated by using the following equation:

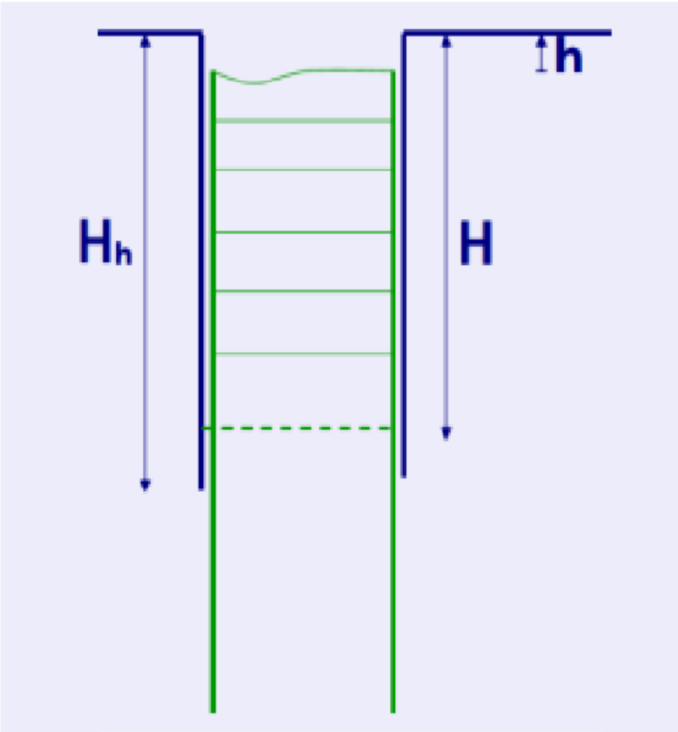


Figure 2 Illustration of parameters affecting the slipform rate (6)

$$V_s = \frac{H-h}{t_s-t_t} \qquad \text{Eq. 1}$$

Where: V_S: $Slipform\ rate\ [cm/h]$

t_S: $Setting\ time\ [h]$

t_t: $Time\ from\ mixing\ concrete\ to\ placing\ [h]$

H: $Distance\ from\ the\ top\ of\ the\ panel\ to\ the\ curing\ front\ [cm]$

h: $Distance\ from\ the\ top\ of\ the\ slipform\ panel\ to\ the\ freeboard\ [cm]$

$H < H_h$

Where H_h: $Height\ of\ slipformpanel\ [cm]$

2.2. Fresh concrete properties

2.2.1. Introduction

Concrete is a material that is continuously developing/changing. This "life cycle" can be divided up into three main phases: fresh phase, hardening phase, and service phase. The fresh phase further can be divided in to two: the plastic(liquid) phase and semi plastic (semi liquid) phase.

The plastic phase involves mixing, transport, casting, and early setting/stiffening in the mould (form work). Hydration takes place slowly during this period. In the mould, the concrete gradually loses all consistency due to weak physical bonds between particles and initial hydration products (semi-plastic phase) (1).

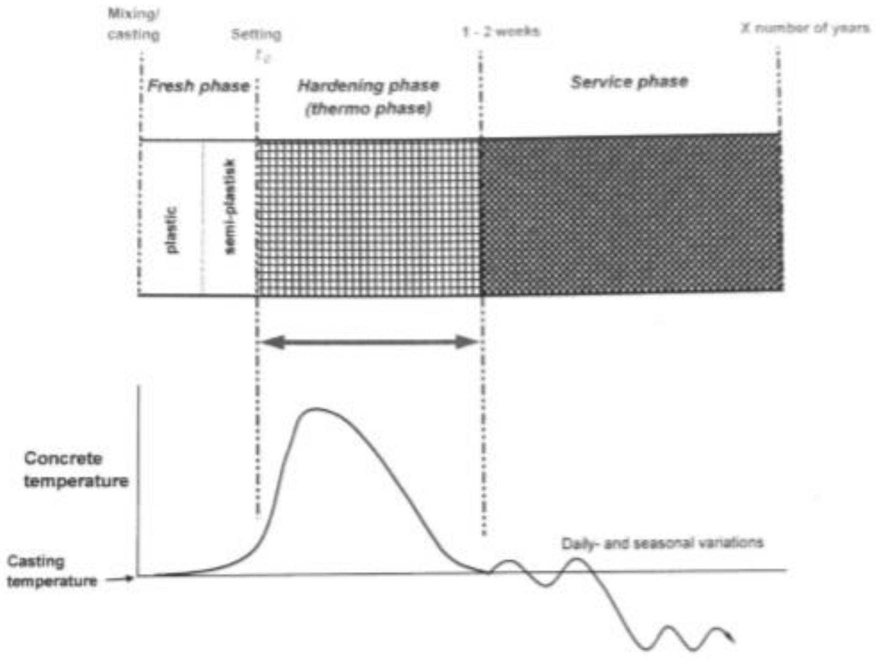


Figure 3 Different phases of concrete and temperatuer development (1)

At point t_o in time, hydration has come far enough to gain measurable mechanical properties in the concrete. The time t_o is related to 'final setting' and can be regarded as the start of the hardening phase and varies with the temperature of the concrete, types of cement/binder and additives (1).

During slip forming, the fresh concrete in the interfacial zone will be exposed to shear stresses because of the friction that occurs during lifting of the slipform panel. If the friction force is at the same level as the shear strength, the concrete will displace or flow in the interfacial zone when the panel is lifted. When the friction force is lower than the shear strength, the friction force will be transferred as shear stress into the cover zone.

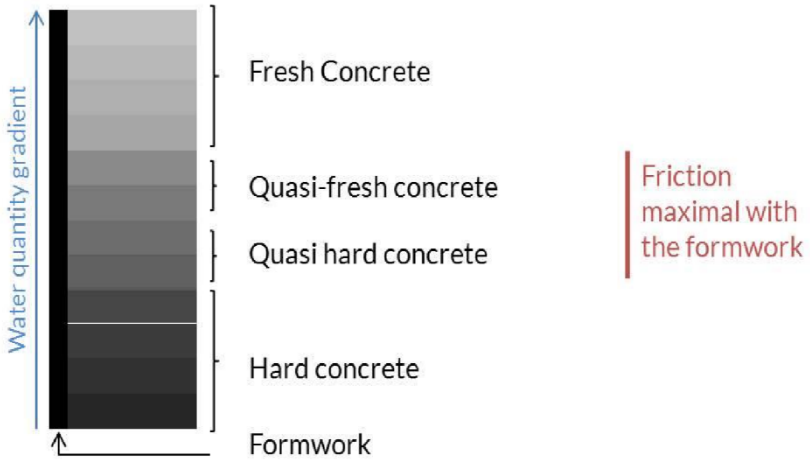


Figure 4 Concrete evolution inside a slipform formwork (7)

However, it is only the particles in the fresh concrete that can resist and transfer the shear stress. The water cannot transfer shear stress, but it can transfer pressure (positive as well as negative). Since the shear stress depends on the actual particle pressure, the parameters affecting the pressure between the particles must be taken into consideration when evaluating the shear stress in the concrete (3).

2.2.2. Parameters affecting the particle pressure in fresh concrete

Fresh concrete is a material that instantaneously imposes shear strain when stress is applied. When the shear stress is below the yield value, the concrete behaves like an elastic solid. With higher shear stress, the bond strength between the particles is insufficient to prevent flow and the concrete will gradually change to a more liquid like consistence (3).

The shear strength in fresh concrete mainly affected by **cohesion** and **internal friction** between the particles. At the early stage (liquid phase), the shear strength is low due to low cohesion and low internal friction between the particles. During the semi-liquid phase, the shear strength increases due to higher cohesion created by the cement water reactions (hydration). And the internal friction also become higher because of higher effective pressure (3).

Cohesion and Internal friction in concrete

The main source of cohesion in concrete is chemical bonding between particles in liquid suspensions because of the hydration of the cement. the cohesion is too low to counteract the effect of different densities between the concrete constituent. The chemical bonding will be small when the concrete is fresh and increase with time as the hydration proceeds. In general, the cohesion will increase with decreasing particle size, because the ratio between the surface area divided by volume is increasing (3) (1).

The shear strength of fresh concrete is mainly due to the internal friction because of particle interaction and the magnitude of the internal friction depends on the shape of the particles, particle size distribution, packing of the particles and the friction coefficient when sliding between the particles. The angle of friction (φ) will increase with increased sharpness and roughness of the particles, increased packing, and increased friction coefficient. The internal friction will also increase with increasing effective pressure (3).

2.2.3. Effective pressure and Normal pressure

As illustrated on Figure below and following Terzaghi's assumption, the effective stress is the average grain to grain pressure and can be calculated from the total stress and interstitial fluid pore pressure.

The effective stress is pushing on the area A whereas the water pressure acting where the water network is continuous that means subtracting the granular contacts area (A-Ac). The force of the pore water pressure is expressed in Eq. 2.

$$F_{uw} = (A - A_c) * u_w \qquad \text{Eq. 2}$$

The force effective stress:

$$F_{\sigma'} = A * \sigma' \qquad \text{Eq. 3}$$

The normal force:

$$F_N = F_{\sigma'} + F_{uw} \qquad \text{Eq. 4}$$

From the above equations we can calculate the effective stress as:

$$F_N = A * \sigma' + (A - A_c) * u_w \qquad \text{Eq. 5}$$

$$\sigma' = \frac{F_N}{A} + u_w * \frac{(A - A_c)}{A} \qquad \text{Eq. 6}$$

And Ac is assumed to be small compared to 'A' even when Ac will increase with hydration (6), thus Terzaghi's equation can be written Eq. 7.

$$\sigma' = \sigma - u_w \qquad \text{Eq. 7}$$

σ = total pressure

σ' = effective pressure

u_w = pore water pressure

The total stress of the concrete is considered in this study almost constant. Therefore, the effective pressure of the concrete only varies with concrete pore pressure. Terzaghi equation is illustrated in Fig. 5. At constant total pressure, negative pore water pressure increases the stress σ' acting on the granular skeleton (which is the case in the early stage of hydration).

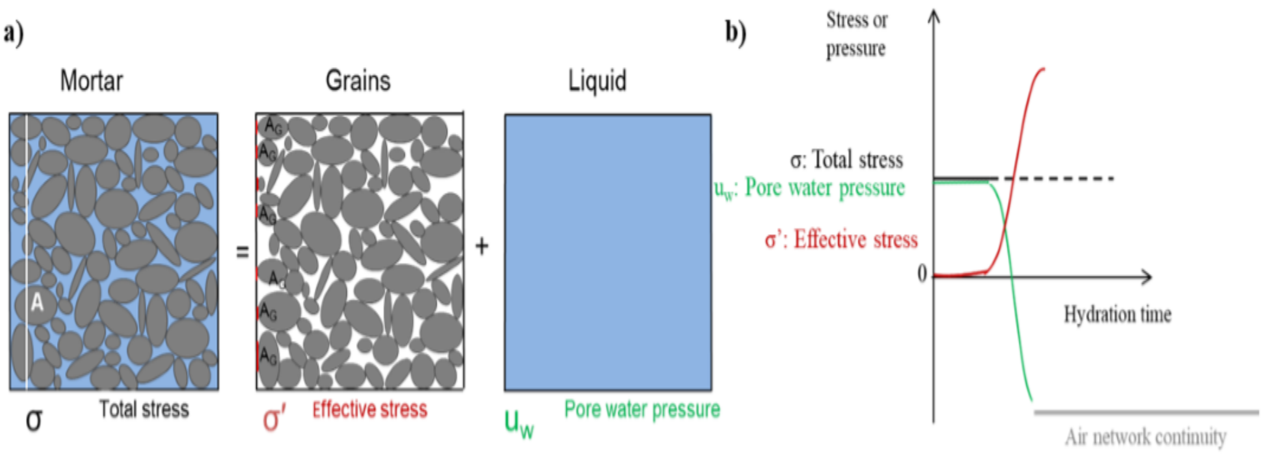


Figure 5 The pressure through the particles and water phase (7)

2.2.4. Porewater pressure

Water pressure variations can be considerably larger than the normal stress variations (induced by the weight of the material) recorded during the slipforming operation. Therefore, water pressure variations are mainly responsible for the increase of effective stress and thus the increase of friction. It is important to note that the effective stress transfers shear stress and not the liquid phase. The following focuses on the pressure of water effect and its origin. (3)

The pore water pressure will vary in the concrete during the period toward setting. In the liquid phase, it is the settlement of the solid particles and bleeding that will affect the pore water pressure. During the semi-liquid phase, it is the cement hydration, re-absorption of water and surface drying that will affects this pressure. The pore water pressure development during the period towards setting and early hardening is shown in Figure 6, for concrete paste.

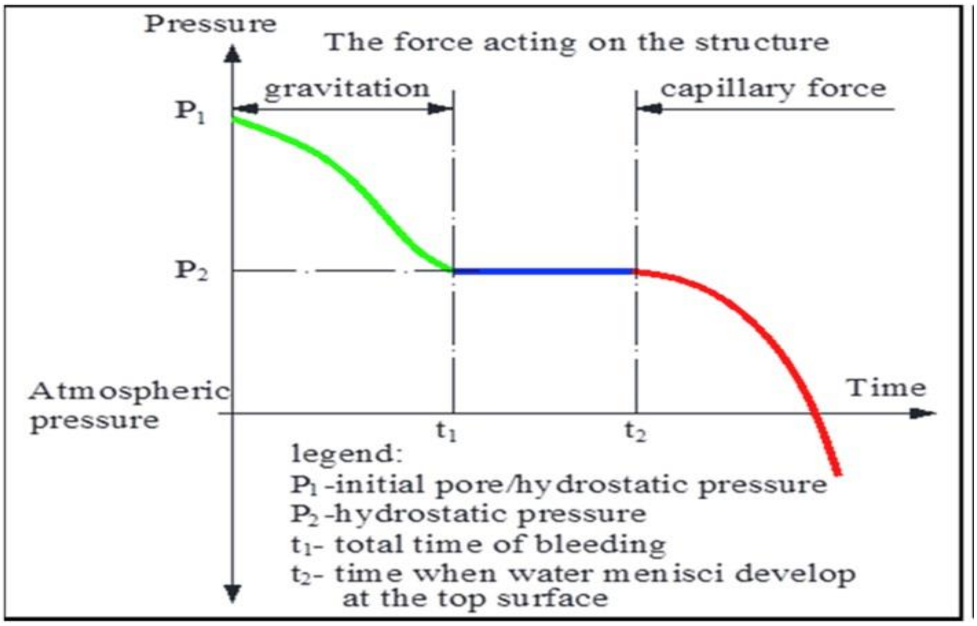


Figure 6 Porewater pressure development in cement paste (9)

The pore water pressure will decrease from P1 to P2 due to settlement of the cement grains after placing. In the same period, bleeding will also occur at the surface. The initial pressure P1 depends on the density of the paste and the depth of the measurement. The surface is covered with bleeding water during the period from t_1 to t_2 and the pore water pressure will remain stable. At time t_2, the surface start to dry out because of free evaporation and the pore water pressure will decrease. The pore water pressure will decrease because of formation of meniscus at the surface and the hydration of the cement (3).

The main reason for the decreasing of pore water pressure in concrete is because of the development of capillary forces. The cause for the capillary forces is self-desiccation in concrete and drying at the surface. The rate of decreasing in pore water pressure due to self-desiccation depends on the cement type and content, w/b ratio and total amount of fines in the concrete mix. A finer pore system will give a higher rate of decrease in pore water pressure.

The sum of the initial volumes of water and cement is larger than the volume of the formed hydrates; this is called Le Chatelier contraction or self-desiccation.(see the reactions below) with contraction and hydrates formation, the grains will come closer together (7)

The main hydration reactions of the Portland cement from the most reactive hydrate to the less one is presented below:

$3CaO.Al_2O_3$ (C_3A)+ $3CaSO_4.2H_2O$ + H_2O => $C_3A.3CaSO_4.32H_2O$ (ettringite)
$3CaO.SiO_2$ (C_3S alite) +5.3 H_2O => $C_{1.7}SH_4$ (CSH) + 1.3 $Ca(OH)_2$ (Portlandite CH)
$2CaO.SiO_2$ (C_2S belite) + 5.3 H_2O => $C_{1.7}SH4$ (CSH) + 0.3 $Ca(OH)_2$(Portlandite CH)
$4CaO.Al_2O_3$ Fe2O3 (C_4AF) reaction (with gypsum $CaSO_4$) is less reactive.

When the sample becomes harder, there is a percolation of the grains and the air will occupy the difference of water volume. Thus, the pressure of water will be in de-pressure compared to the atmospheric pressure.

For surface drying the pressure development depends on the rate of evaporation, pore system and the particle geometry at the concrete surface.

2.2.5. Interaction between concrete and formwork

Concerning moving formwork, it has been shown that the roughness of the formwork has an influence on the interfacial behaviour.

The two physical phenomena which increases the frictional force at the surface of a sliding formwork and concrete are effective stress and adhesion. The origin of adhesion is the cement hydration and it is mainly affected the static friction. It firstly induces water consumption thus suction, (because of Le Chatelier contraction, see above) and hydrates formation which may bond to the surface. (7)

During sliding, possible micro-cracking/lump formation can happen on the wall surface. These defects are most probably related to the concrete adhesion on the formwork. These issues should be reduced and prevented to avoid a reduction of the durability of the structures that could turn into strong damages if not properly treated. (7)

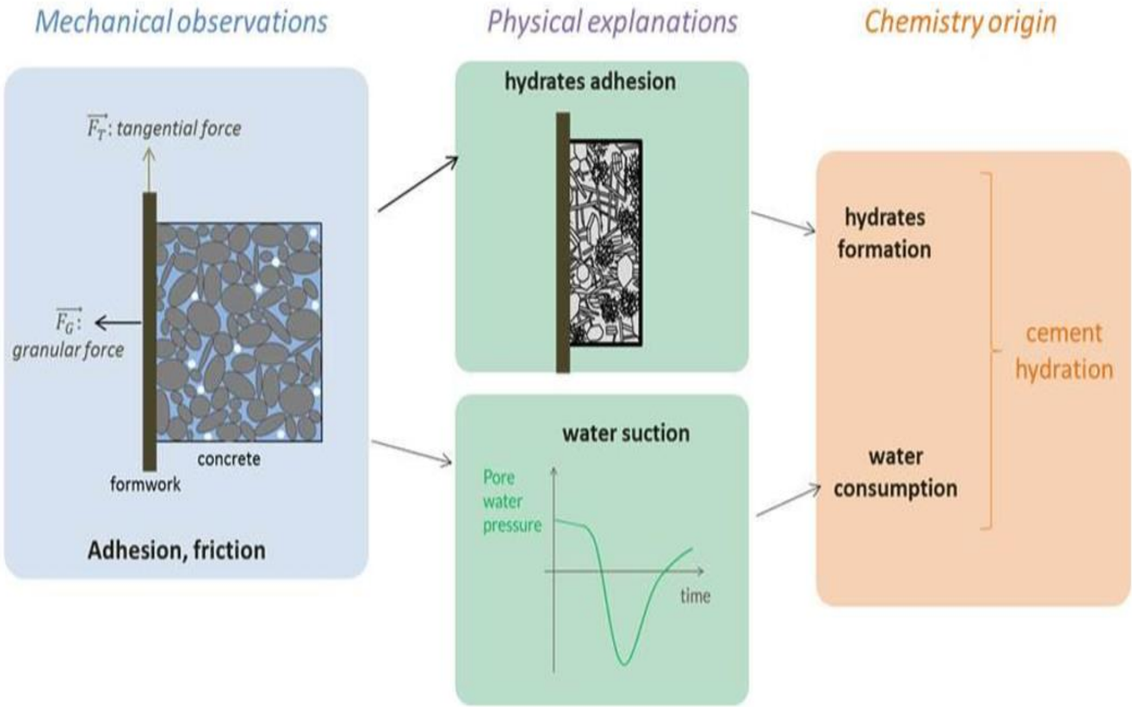


Figure 7 Summary of granular (effective) forces origin (7)

The particularity of slipforming technique is that the walls are composed of a material exhibiting a gradient of hydration state with concrete shifting from fresh state to early age (Fig. 6). Usually, the formwork is about 1.2 meters length, the concrete must be set at the bottom of the formwork. The average speed is around 15 - 25 centimetres per hour (7). It has been shown that water consumption caused by cement hydration induces capillary suction which is assumed to play a major role on the interface.

2.2.6. Effect of concrete mix-design on interfacial behaviour

a) Granular packing influence on pore water pressure and rheology

The granular packing has an influence on friction because it has an influence on concrete rheology and pore water pressure. This is illustrated for example on Figure below, (8) compared the pore water measurement with 5, 10 and 15% of silica fume. It is observable that the finer the skeleton, the faster the pore water pressure decreases. In the experimental part, the fineness of the skeleton will be changed.

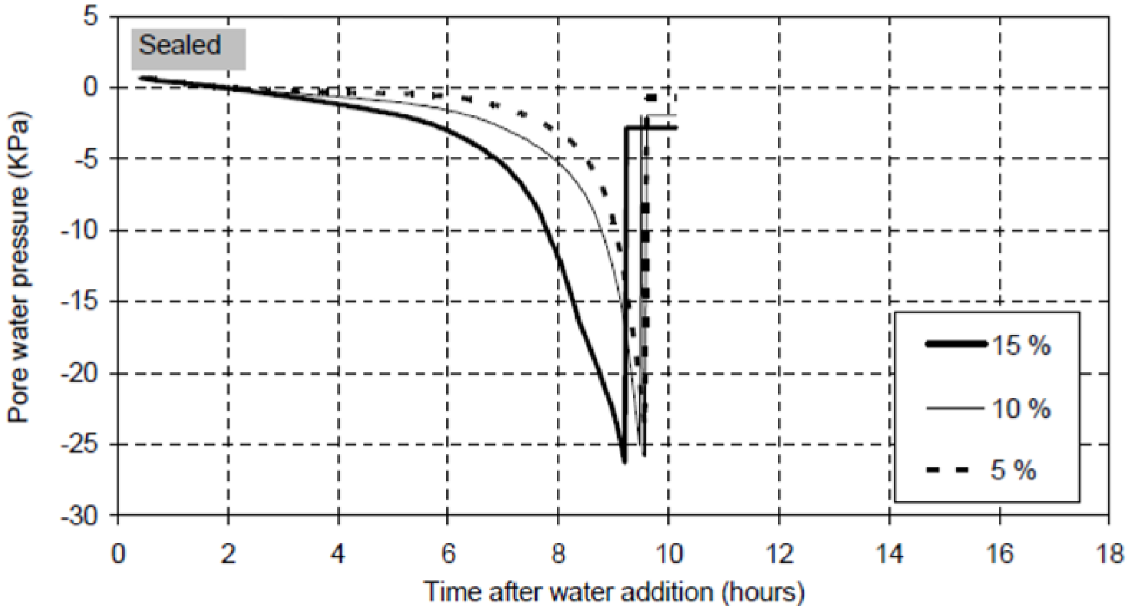


Figure 8 Porewater pressure development in concrete with different amount of silica fume (8).

Figure 9 below shows that the development of the capillary pressure in cement paste and a fly ash slurry. This shows very clearly that the rate of pressure progress is much higher in cement paste with w/c ratio of 0.35 than in fly ash slurry, in spite of the fact that the fly ash and the cement of type P have an equivalent specific surface areas and that the initial porosity of past P9 is higher than that of the fly ash slurry. This behaviour can be explained by difference in the particle shape, surface quality and interparticle forces between the cement and the fly ash, as well as the chemical reactions between the cement and the mixing water (9).

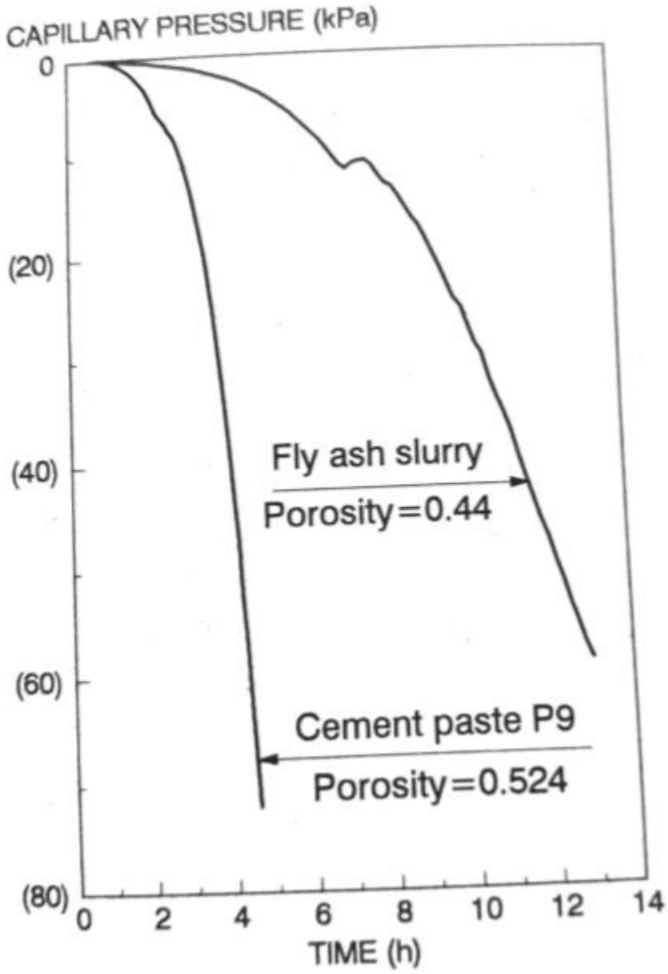


Figure 9 Development of the capilary pressure in cement past and fly ash slury (9)

b) Water cement (w/c) ratio influence

Figure 10 shows that higher concentration of the cement in the paste will result in a higher initial pore water pressure because of the density of the paste is highest for the paste with highest cement concentration. In this instance, the rate of settlement is almost the same in all tests. The settlement and bleeding period will end no later than at the beginning of the semi liquid phase. At that time, the concrete will be rigid enough to withstand any further internal deformation primarily caused by the force of gravity (3).

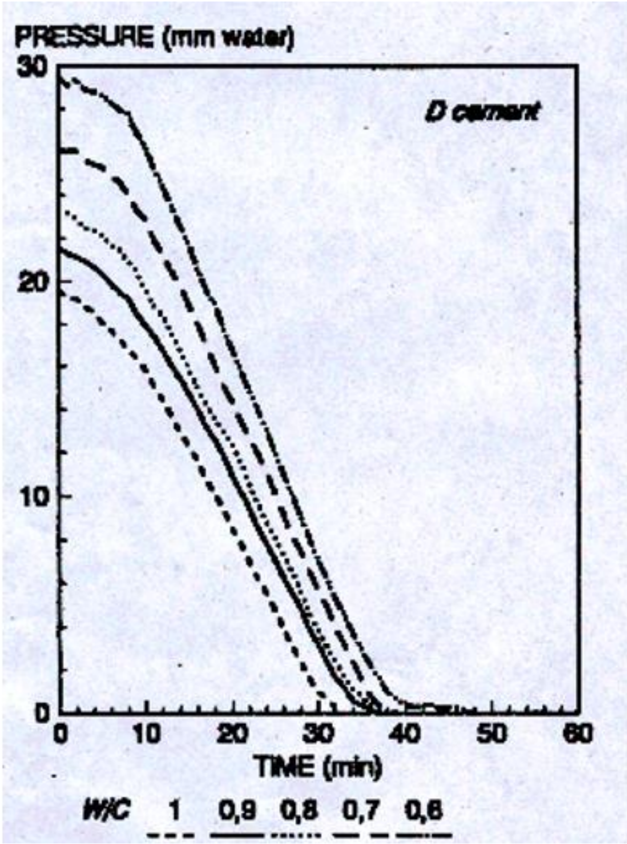


Figure 10 Porewater pressure development with different w/c in cement paste (3).

2.2.7. Static and sliding friction

The lifting operation of slipforming is carried out from liquid state of fresh concrete to a setting state where it has reached an almost elastic solid-state. It can be noted that between those two extreme states, the concrete exhibits different frictional resistance. The lifting force must overcome the adhesion and the internal friction due to the effective pressure before the sliding starts. This peak frictional force at the start is called static lifting force. After the first movement, the force required to lift the plate is decreasing due to the reduction of adhesion (mostly depends on the surface roughness). The minimum friction that occurs during sliding is called sliding lifting force. The difference between the static lifting force and the sliding lifting force will be the force of adhesion and the sliding lifting force resulting is only due to the effective stress (7). Figure 11.

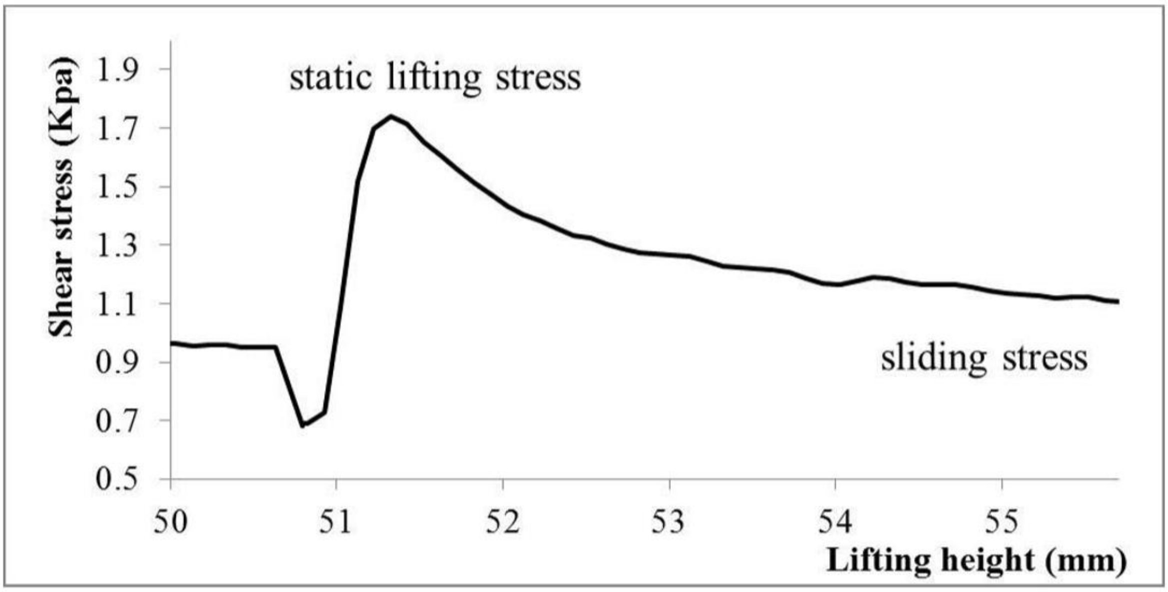


Figure 11 Illustration of static lifting stress and sliding stress (7).

During one cycle (Fig. 11), it seems that the formwork movement induces a shear stress reduction. It has been shown in that the lifting force is proportional to the effective stress of the concrete on the panels. The relation is described by the adhesion and friction laws:

$$F = \mu \cdot N \qquad \text{Eq. 8}$$

where F = friction force

N = normal force

μ= friction coefficient.

The friction coefficient is the coefficient of static friction or sliding friction.

$\mu_H > \mu_G$, where μ_H is static friction coefficient μ_G is sliding friction coefficient

3. Description of slipform rig

3.1. General

The objective of the vertical slipform rig is to identify parameters affecting the friction. This also includes a study on how the parameters affect the friction. Connection between friction and any surface damages will also be investigated. The test program will be focused on parameters in the fresh concrete and slipform technical parameters such as: porewater pressure, lifting forces and frequency.

The purpose for the rig is to simulate realistic loads that one or several layers of concrete is exposed to during slipforming. The slipform panel is installed vertically, which means that the concrete pressure will depend on the concrete properties and the inclination and stiffness of the slipform panel. The panel has the possibility to adjust both the inclination and the stiffness to simulate different slipform set-ups. (3)

Figure 12 Slip form rig

3.2. Concrete container

The concrete container is located inside the steel framework. It is 600 mm wide and 300 mm deep and 1000mm high. The maximum capacity of the container is 180L.

Figure 13 Concrete container

3.3. The slipform panel

The slipform panel is made from a plywood board covered with a steel plate, it has a length of 2000mm and width 600mm. This makes the maximum height the slipform panel can be lifted 1000mm, but due to necessary margins the panel is not lifted higher than 930mm.

An electric engine lifts the panel with the desired frequency and height with precision. The slipform panel was under testing lifted 12mm and then lowered 2mm to imitate the locking mechanism of jacks used in slipforming. The panel was lifted every 15 minutes, giving the rig a slipform-rate of 40mm/h. (6)

3.4. Normal force measurement

At the back side of the slipform panel, four load cells are installed. The upper two load cells are installed 650 mm above the bottom of the container and the lower load cells are installed 70 mm above the bottom. They are placed in two rows with two transducers each, centred 400mm apart. The load cells are rolling along the flat steel where the inclination can be adjusted relatively to the slipform panel, see Figure 14.

The four load cells will measure the concrete pressure and the pressure distribution against the slipform panel.

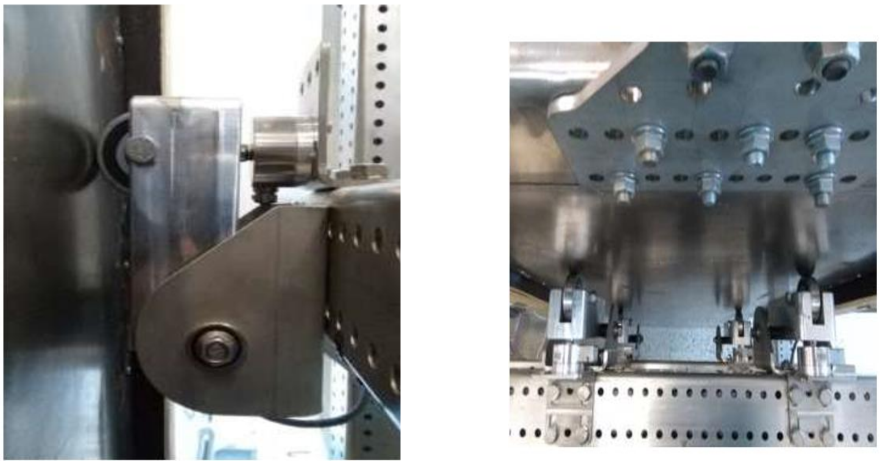


Figure 14 Position of the force transducers measuring the normal pressure

3.5. Temperature development measurement

The temperature development of the concrete was measured using the measuring instrument Type T Thermocouple (Copper/Constantan)). This meter is given with a measurement spectrum between -200 C and 350 C (10). In experiments two of these meters were used. Both were pushed about 10 cm into the concrete and placed in the middle of the sample at about 20 cm intervals. There is no logical explanation for why these should give different results. In all experiments we observe that the two temperature graphs differ somewhat in relation to each other, but they always have the same curve and evolution. There is therefore reason to believe that this gap is due to slightly different calibration, which gives slightly different graphs as they may then have slightly different references. The temperature results taken are an average of these two.

Figure 15 Temperature measurement

3.6. Pore water pressure measurement

The pore pressure in the sample was also continuously monitored during the test period. This measurement was done using a pore pressure gauge which records pore pressure up to 10 bar.

The gauge consists of a 10 cm metered steel tube with an internal diameter of 3 mm. The system relies on being free of air to record correct readings. It is therefore mounted under water before being introduced into the sample. The meter is fed into the sample at a height of 20 cm above the floor of the mould, and 9 cm from the sliding panel. The distance to the sliding panel must be sufficient so that the measurements are not disturbed by any pore pressure change because of the sliding panel being moved (10).

4. Concrete constituency

4.1. Concrete mix

The reference concrete mixes used on the experiment are taken from **E39 Sulafjorden** (table 1). The mixes are environmentally friendly concrete with different amount of fly ash content. This concrete is modified according to the availability, type, and moisture content of materials at the laboratory of University of stavanger (table 2) without changing the properties and used when the effects of the slipform technical parameters on the friction are tested. The modified concrete is also used during the fresh and hardened concrete properties testing.

Table 1 Concrete mixes from E39 Sulafjorden

Kg/m^3	**Mix-3**	**Mix-4**	**Mix-5**	**Mix-6**
w/b-ratio	0.35	0.3	0.35	0.3
Clinker	382	410	287	307
Fly ash total	67	72	159	169
Cement	449	482	338	361
Silica	14	15	14	15
Fly ash added	-	-	108	115
Sand 0-8	877	875	877	873
Gravel 8-16	948	946	949	944
Water	167	154	155	141
RMC315	4.4	7.5	6.7	10.2

Table 2 Modified Concrete mixes according to availabilty of materials at UiS

Kg/m³	**Mix-3**	**Mix-4**	**Mix-5**	**Mix-6**
w/b-ratio	0.35	0.3	0.35	0.3
Clinker	382	410	287	307
Fly ash total	67	72	159	169
Cement	449	482	338	361
Silica	14	15	14	15
Fly ash added	-	-	108	115
Sand 0-8*1	909	907	909	905
Gravel 8-16	948	946	949	944
Water*2	135	122	123	109
PL/Dynamon SX-N*3	4.4	7.5	6.7	10.2

*1 moisture content of sand at Uis 3.5%, *2 modified amount of water *3 RMC 315 is replaced by PL/Dynamon

Due to the limited capacity of the mixer and the concrete container of the slipform rig, 120 litres of concrete for each mix was used to carry on the experiments. (table 3).

Anleggsement FA (CEM II/A-V 42,5 N) with 15% fly ash content is used at the laboratory which is the same proportion of clinker and fly ash as in the reference concrete mix.

Table 3 Concrete mix for 120Lit

Kg/120lit	**Mix-3**	**Mix-4**	**Mix-5**	**Mix-6**
w/b-ratio	0.35	0.3	0.35	0.3
Anleggsement FA	54	58	41	43
Fly ash added	-	-	12.96	13.8
Silica	1.68	1.8	1.68	1.8
Sand 0-8*1	109	109	109	109
Gravel 8-16	114	114	114	113
Water*2	16.22	14.67	14.78	13.12
PL/Dynamon SX-N*3	0.528	0.9	0.804	1.224

4.2. Materials

4.2.1. Cement

Norcem Anleggsement FA is used in all the mixtures. It is a Portland-fly ash developed for use in civil engineering infrastructure such as bridges and harbour. The cement provides very good workability properties at low water/binder ratios. The heat development is relatively low and is suitable for use in massive constructions. The cement can be used in all exposure, durability, and strength classes. The cement has good workability and resistant properties. (1)

Table 4 properties of Anleggsement FA (CEM II/A-V 42,5N)

Anleggsement FA (CEM II/A-V 42,5N)	
Typical mineral content	
Sulfate, SO_3[%]	≤ 3.5
Chloride, Cl^- [%]	≤ 0.085
Water soluble chromium, Cr^{6+}[ppm]	≤ 2
Alkalies, Na_2O_{ekv}[%]	0.6
Clinker [%]	85
Fly ash [%]	15
Physical properties	
Fineness [m^2/kg]	390
Specific weight [kg/m^3]	3.02
Initial set [min]	165

4.2.2. Aggregate

Aggregate is a common name for sands and rock materials used in concrete. Usually, the aggregates occupy between 65% and 75% of the concrete volume. The aggregate influences both the fresh and cured concrete properties.

The aggregate used in the concrete mix for the experimental test in the vertical slipform rig is from Årdal and has mostly a natural round grain form with sizes of 0-8mm fine aggregates (sand) and coarse aggregates 8-16mm.

4.2.3. Pozzolan

Pozzolans are a material that react with water and calcium hydroxide and creates compounds possessing cementitious properties. They are often by-products from industry that are added to the concrete to reduce the quantity of cement in the mix. Two regular pozzolans used in concrete are fly ash and silica. (6)

$$2SiO_2 + 3Ca(OH)_2 \rightarrow 3CaO * 2SiO_2 * 3H_2O$$

$$2S + 3CH \rightarrow C_3S_2H_3$$

$$Silica + calcium\ hydroxide \rightarrow C - S - H$$

The main three types of pozzolanic additions are: fly ash, silica fume and blast-furnace slag. All 3 of these are industrial by product. When used in concrete they reduce the demand for Portland cement clinker. Hence their use is advantageous both from economic and environmental points of view-particularly with respect to reducing the large amount of CO_2 emission associated with Portland cement production (1).

The main purpose of this study focusses on environmentally friendly concrete design. Therefore, fly ash is used in significant amount to reduce the Portland cement clinker.

Fly ash is a by product of power station furnaces fired by pulverized bituminous coal. It replaces portion of concrete and hence improve sustainability of structures. Any replacement percentage can be considered provided that project requirement and specifications are not compromised. For example, concrete strength shall be the same of nearly the same of concrete without replacement materials.

Generally, fly ash reduce heat of hydration, improve sulfate resistance, reduce chloride diffusivity, minimize risk of alkali aggregate reactivity, environmentally friendly, and improve concrete economy.

Micro silica is also used in the concrete mix which is finer than fly ash. The small size makes micro silica very efficient filler, which possibly serves to distribute the binder phase(C-S-H) in a more homogeneous manner in the space available. It has been shown the silica fume does not decrease the total porosity of the binder to water but subdivides the pore volume into finer pores. Thus, both the pozzolanic reaction and the filler effect combine to produce the improved properties of hardened concrete (1).

4.2.4. Admixture

Admixtures is materials that are added during mixing in small amounts relative to the amount of cement to modify the properties of fresh or hardened concrete. Regular admixtures are plasticizer and superplasticizer, air entraining, accelerating and retardation (6).

In the given concrete mixes RMC 315 plasticizer is used but, in this experiment a Dynamon SN-X is used, a superplasticizer based on modified acrylic polymers, which is nearly equivalent in property. It is added to the concrete primarily to maintain workability

4.3. Testing of fresh concrete

4.3.1. Slump flow test

The slump-flow test gives an indication on the consistence of the concrete. The test was performed according to NSEN 12350-2:2009.

Slump cone is placed on a flat and non-water absorbent surface and filled with concrete, in this case the cone is filled with out tamping in layers, the cone is lifted slowly, vertically upwards without twist. The cone is placed next to the concrete sample and measure the difference in height between the cone and the top point of the concrete sample. The slump-flow is the diameter of the concrete on the surface.

Figure 16 slump flow test

4.3.2. Air content and density

Natural air voids content is in most cases between 2% and 3% for ordinary structural concrete. If the air void content increases to more than 5% it can be difficult to obtain good enough flow ability due to increased cohesion but in other hand it can improve the stability of the concrete due to cohesion.

Air content measurement was done according to NS-EN 12350-7:2009, using cover assembly with pressure gauge with the corresponding 8 litre bucket for concrete.

In the case of self-compacting concrete, the container shall be filled in one operation and no mechanical compaction shall be applied during filling or after the container is filled. After the container is filled, strike off level and smooth the surface with the steel trowel. The flanges of the container and cover assembly are thoroughly cleaned. The cover assembly is clamped, sealing the container. Using a syringe, water is injected through one of the two open valves until water emerge from the other valve. Air bleeder valve is closed, and air is pumped into the chamber until the hand on the pressure gauge is on the initial pressure line. After tapping on the container, stabilize the hand on the pressure gauge is on the initial pressure line by further pumping in or bleeding off air. At last the main valve is opened and read the apparent percentage of air

Figure 17 Air content and Density measurement

Measurement of the density of fresh concrete was made according to the NS-EN 123506:2009, using the 8-liter bucket. This test was done together with the air content test because the bucket used was the same. The empty 8-liter bucket is weighed on a scale. The bucket is then filled with fresh concrete. The edge is cleaned, and the bucket is weighed again. From the mass and known volume of the bucket, the density is calculated.

4.4. Casting

4.4.1. Cubes

A total of 3 cubes were made for each mix of concrete according to NS-EN 12390-2:2009. The moulds (100x100x100 mm) were cleaned and with form oil to prevent adhering to the mould. Due to the use of self-compacting concrete the mould is filled in one operation and no mechanical compaction is applied during filling or after the mould is filled. The surface is levelled with a steel trowel and covered in plastic. The specimens are left in the mould over night at a temperature of 20±5ºC and are then removed from the mould. The specimens are then cured in water at a temperature of 20±2ºC for a total of 28 days (11).

4.4.2. Slipform rig test

Before the test was performed, all the surfaces of the slip form test rig were cleaned, and any loose particles are removed. The concrete container is coated with form oil (with exception of the steel panel) to ease the removal of the concrete block after the test. The sensors are then zeroed, and the registration is started. The concreate is poured into the container and hand compacted to make sure of good casting. Two temperature gauges are placed into the concrete, approximately 100mm under the surface. A bolt is placed in the concrete to be able to lift it out after the test.

The slipform lifting program is started. The test is then in progress to the next day. When the panel is lifted to the top, the registration is manually stopped, and the data is saved. The concrete block is then lifted out of the rig with the help of a forklift. The container and panel is cleaned (6).

4.5. Compresion strength test

The concrete test cubes are crushed in a compression test machine in accordance with NS-EN 12390-4. The largest tolerated load is recorded and the compressive strength (σ_{m}) is calculated for each cube.

$$\sigma_{\mathrm{m}} = \frac{\mathrm{F_m}}{\mathrm{A}} \qquad \text{Eq. (9)}$$

σ_m :- compressive strength [Mpa]

F_m: - fracture force [KN]

A: - cross section area of concrete cubes

5. Result and Discussion

Fresh and hardened concrete properties

In the following tables, different results from the various tests and experiments of fresh and hardened concrete carried out in the laboratory are presented. Brief explanations regarding some of the results are given.

5.1. Slump flow, Air content and Densities

The results from the test of fresh concrete used in the various tests in the sliding rig are presented in the table below:

Table 5 Fresh concrete properties results

Mix	Slump [mm]	Slump flow[mm]	Air content [%]	Densities[kg/m^3]
Mix-3	200	350	2.2	2394
Mix-4	190	330	2.2	2424
Mix-5	250	650	1.0	2418
Mix-6	230	580	3.0	2397

As we can see from the results, the consistency of the concrete mixes 3 and 4 are significantly varied from the original values. This is mainly due to the moisture content of the sand was taken as per the previous measurement data from the laboratory and the second possible reason was the longer time between the addition of water and taking the sample for the test. Taking into consideration these two reasons, the other two mixes was taken carefully, and the values are almost equal to the original. The air content of the mixes also is varied from the original mixes. The densities of the mixes are almost the same to the original mixes.

5.2. Compression strength

The results of the test of hardened concrete used in the various tests in the slipform rig are presented in the table below.

The compressive strength test has not any role in the experiment, where the focus is on the slipform. It is only taken to compare with the given result from the original test given from E39 **S**ulafjorden**.** All the results of compressive strength represent an average of the three test cubes for the respective mixture. Due to the difference of concrete consistency mentioned in the above results of slump measurements in mix 3 and 4 two of the cubes (marked as *) was excluded from the calculation because of irregular shape and size, presumably due to poor compaction during casting.

The test was taken at 55 and 56 days from the casting date because of coronavirus Lockdown so the results are different from the original given mixes of 28 days which is higher in almost all except mix 4.

Table 6 Compresion strength results

Cube no.	Mix-3		Mix-4		Mix-5		Mix-6	
	F_m *(KN)*	**σ_m** (N/mm^2)	**F_m** (KN)	**σ_m** (N/mm^2)	**F_m** (KN)	**σ_m** (N/mm^2)	**F_m** (KN)	**σ_m** (N/mm^2)
1	899.2	89.9	837.4	83.7	847.0	84.7	1021.9	102.2
2	917.3	91.7	724.2*	72.4	864.2	86.4	941.8	94.2
3	836.9*	83.7	810.5	81.1	935.8	93.6	1008.0	100.8
Average	**908.3**	**90.8**	**824.0**	**82.4**	**882.3**	**88.2**	**990.6**	**99.1**

*excluded from the average calculation because the sizes of the cubes were not as the standard.

Slipform rig test results

From the slipform rig, all the observation measured during the experiment are taken as a raw data. This is presented in the form of data records every 0.2 second. These numbers are processed in excel and MATLAB. The easiest way to get an overview of what is going on is achieved by plotting and present the results in graphs.

The parameters recorded and taken from the slip form rig are:

- Three temperature measurements [^{o} C]
- Tension wall (Lifting force) [KN]
- Position (Lifting height) [mm]
- Pore pressure[bar]
- Forces from four load cells [N]
- Time [s]

Several graphs were plotted and presented to compare the results found from different mixes. The development of different parameters in the mixes with same w/b ratio but different amount of clinker and fly ash and effect of one parameter to the other were combined and plotted in the same duration of time.

5.3. Temperature development

The temperature development of all the concrete mixes used at the slip forming rig test is shown in the Figure below.

As shown in the figure, the temperature evolution range in the different mixes is approximately equal, with all samples having a hydration process that begins after about 2-5 hours after water addition. Variation in temperature for the different samples may be due, w/b ratio, amount of clinker and added fly ash and possible variation in room temperature.

Friction increases significantly at the beginning of the hardening process or at the final setting stage of fresh concrete. This occurs when the temperature rises from its dormant stage and reaches the maximum value at the time of maximum hydration process. This shows a correlation between the hydration process in the concrete and the friction between the sliding panel and the concrete surface.

As shown in the figure the evolution of the temperature is higher in the mixes 4 and 6, with higher w/b ratio and relatively lower in the mixes 3 and 5.

The clear relationship between the lifting force and temperature development can be seen in the figures plotted from the raw data in the attachment.

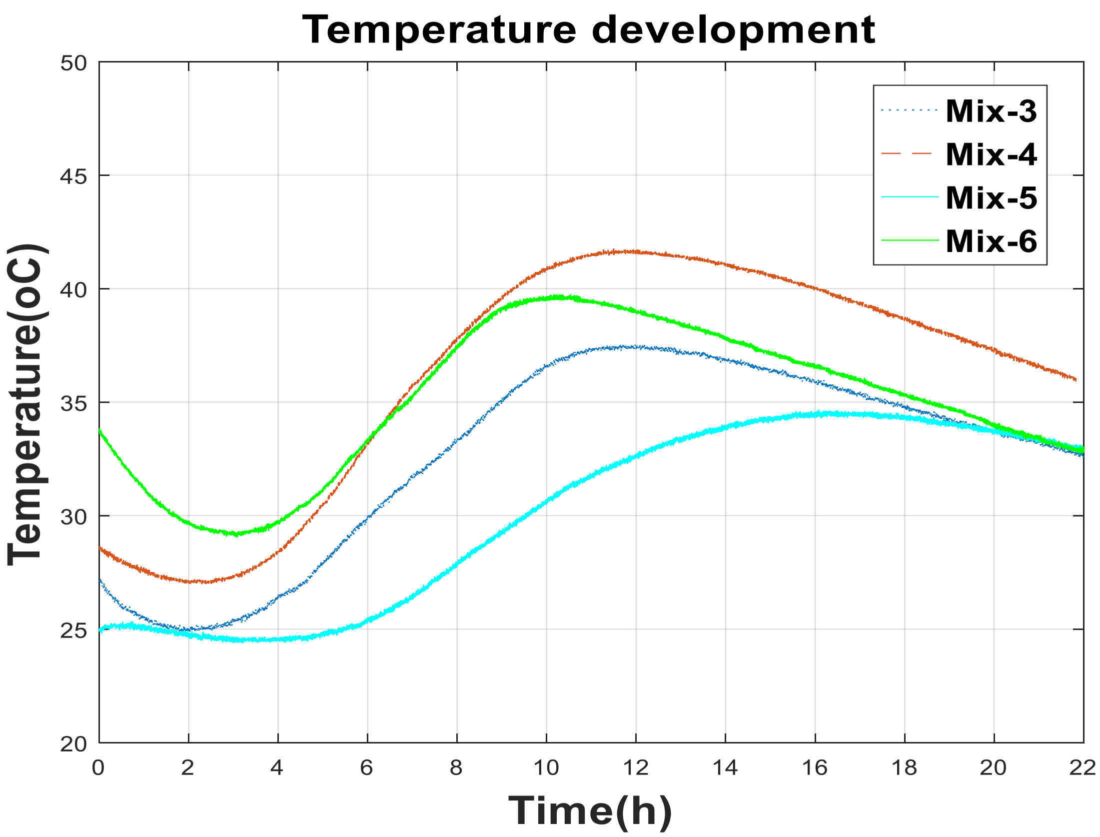


Figure 18 Temperature development of all mixes

In the above results it is shown that the starting temperature of Mix 6 was higher than expected which is around 33 ^{o}C. During the experiment, it is observed that the second measurement was not working properly. So, this high starting temperature could be due to the error made during calibration, but the trend of the curve and evolution of the temperature is the same as the other mixes.

The temperature development of Mix-3 and 5 shown below:

The development of the temperature is higher in mix 3 than mix 5. Both mixes have the same w/b ratio but the amount of clinker in mix 3 is higher than mix 5. The start of hardening or final setting time (according to the theory) is shown to happen earlier at the concrete mix with higher clinker (Mix-3) in this case. This is due to more heat generation at the time of hydration.

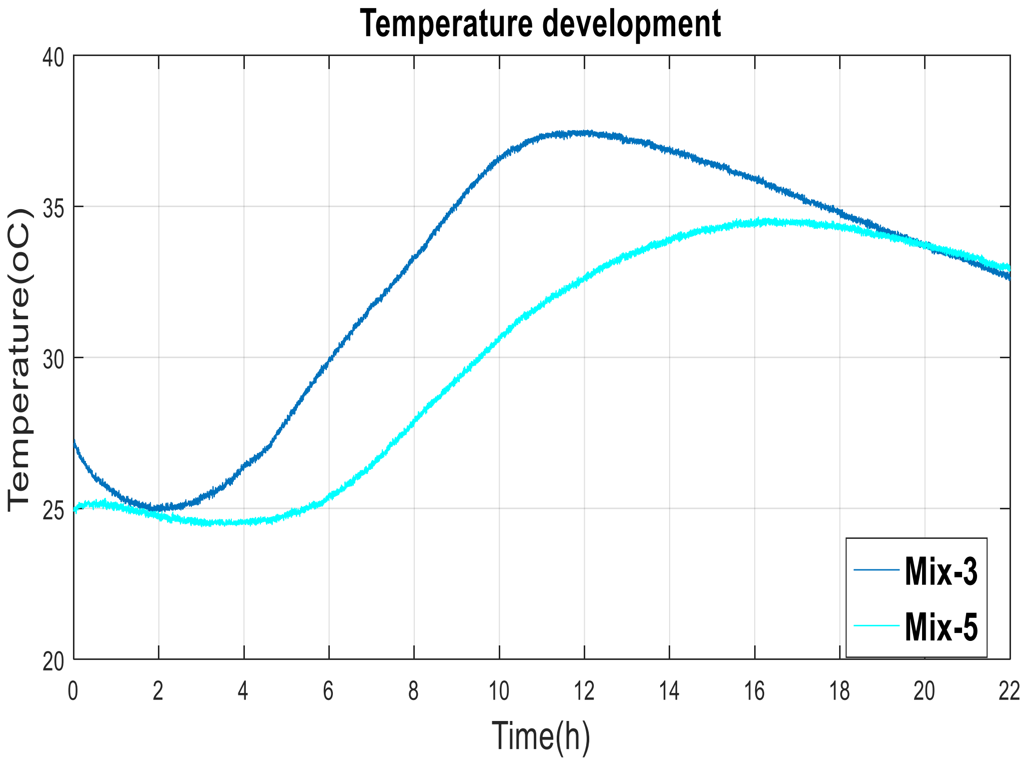


Figure 19 Temperature development Mix-3 and 5

The same trend shown in mix-4 and mix-6 (figure 20) the more the clinker content the earlier setting time or start of hardening.

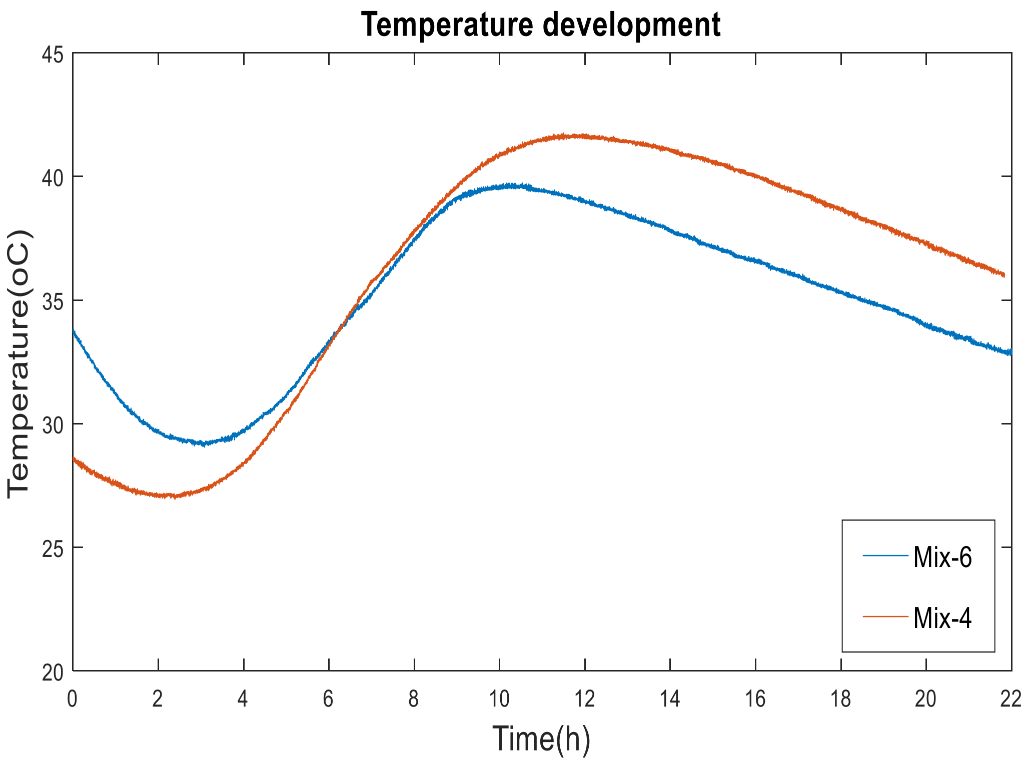


Figure 20 Temperature development Mixes 4&5

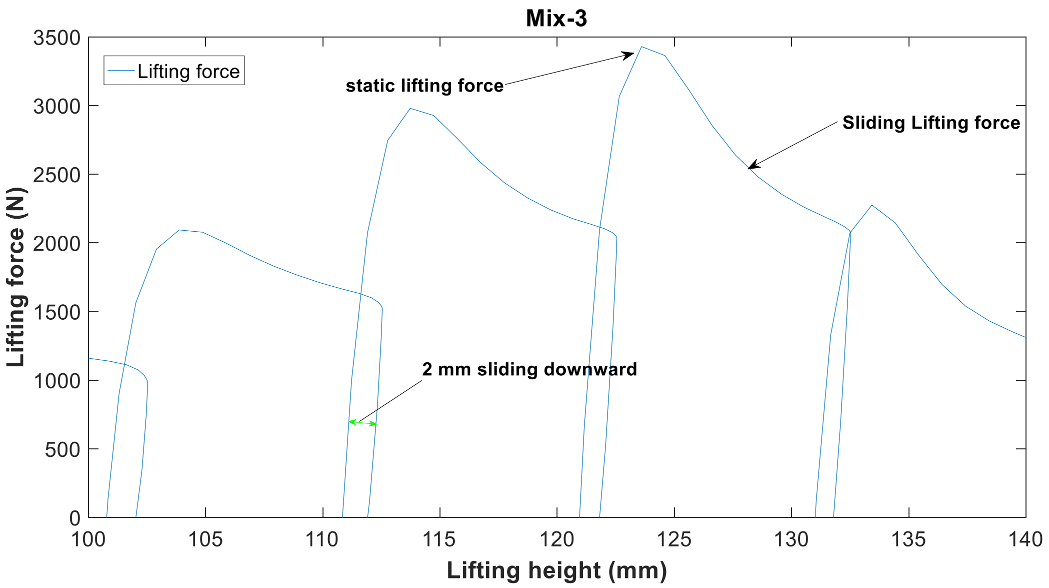
5.4. Lifting force

The figures below show the development of lifting force as the lifting of the slip form panel proceeds during the test for Mix-3 for one hour.

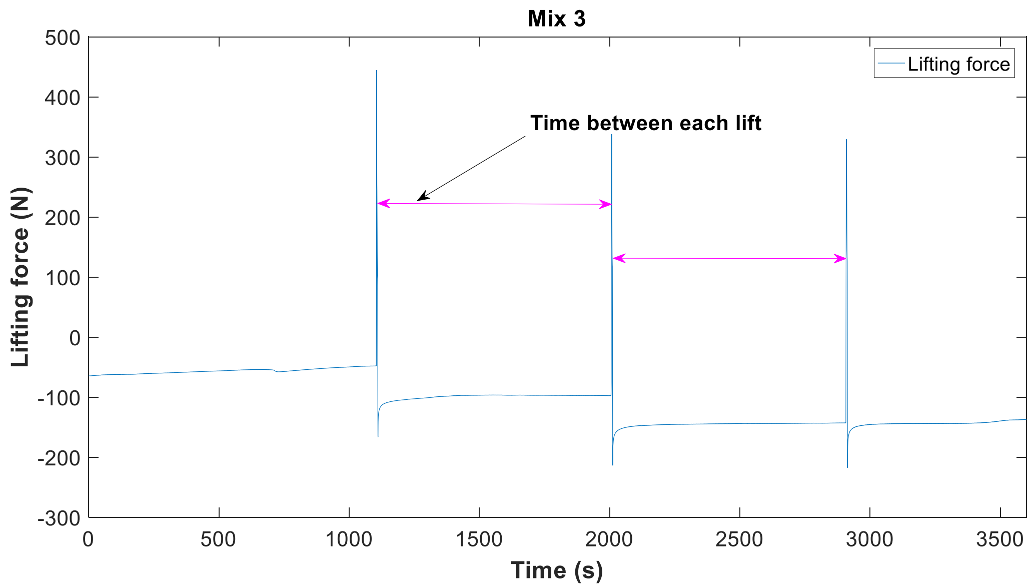
Before each lift, the lifting force must exceed the friction and adhesion forces between the concrete and the sliding panel. As the panel starts sliding, the lifting force is higher than when the panel is sliding. This critical high frictional force is defined as the static friction (12). After starting up, the panel begins to slide along the concrete surface, and the frictional force decreases and stabilizes until just before the next lift. The lowest frictional force during this period is called sliding friction.

An example on identification of the static and sliding lifting force for a single lift is shown in Figure 21(a).

a)



b)



C)

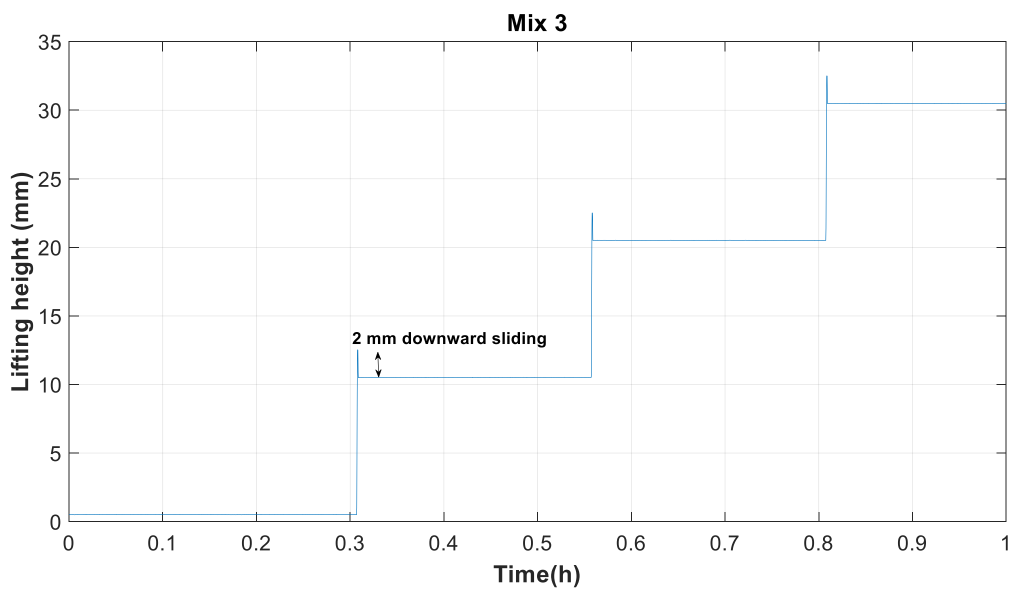


Figure 21 a) Static and Sliding Lifting force , b) Time between each lift, c) Lifting height

The lifting of the panel is carried out at regular intervals depending on the slipform rate. The lifting height can be adjusted from 10 to 25 mm depending on the desired frequency of the lifting. With a hydraulic system, the lifting operation is carried out by increasing the oil pressure. When the oil pressure is sufficient to overcome the friction and the weight of the form, the slipform will start to lift. After the slipform is lifted, the form is let down until the breaks in the jacks are activated, normally 2 mm downwards (3).

The following figures are the development of lifting force and normal concrete force in each mix. The normal force in all the tests was maintained constant manually.

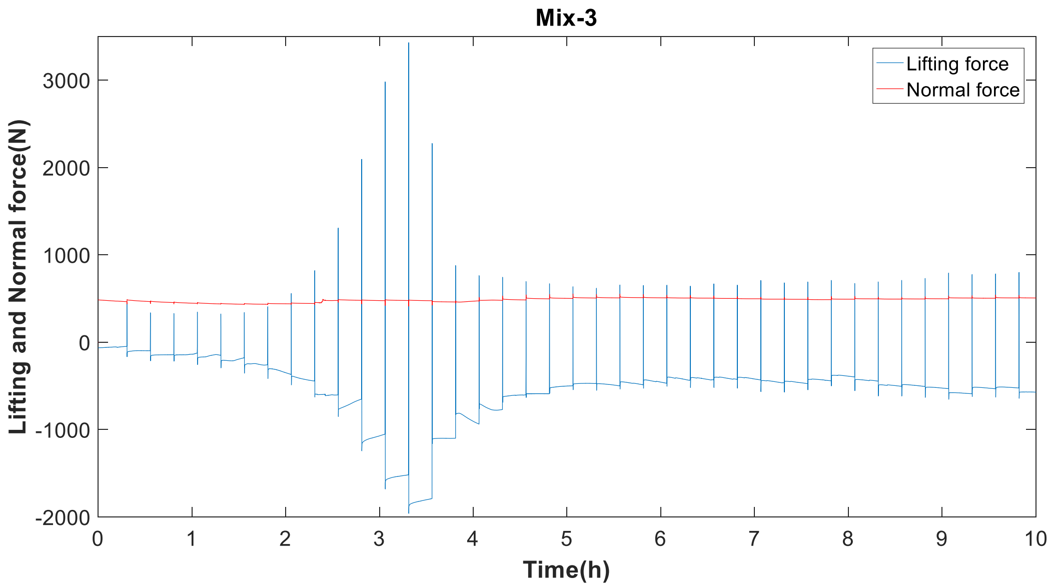


Figure 22 Lifting and Normal force mix 3

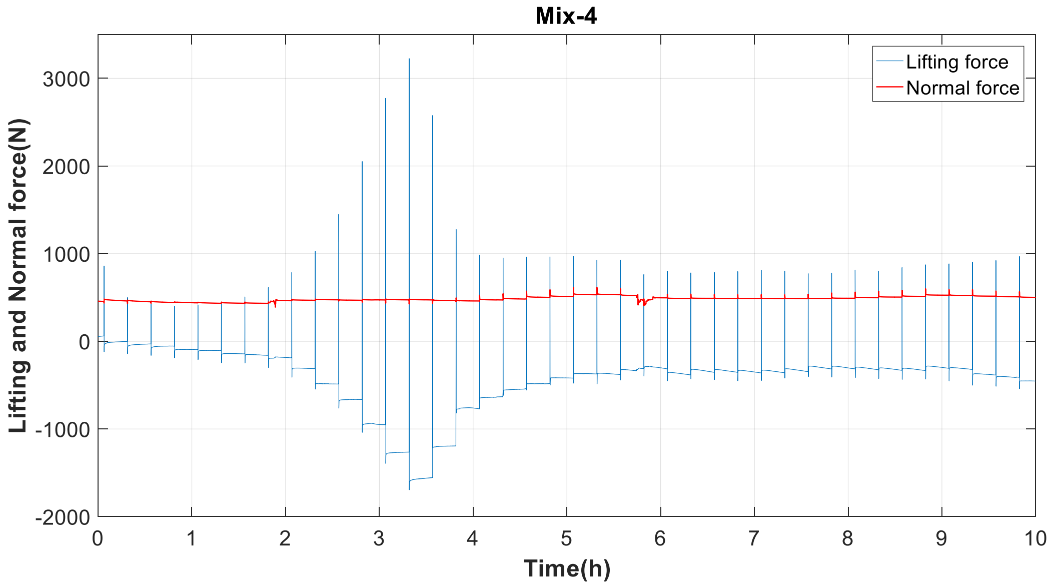


Figure 23 Lifting and normal force mix 4

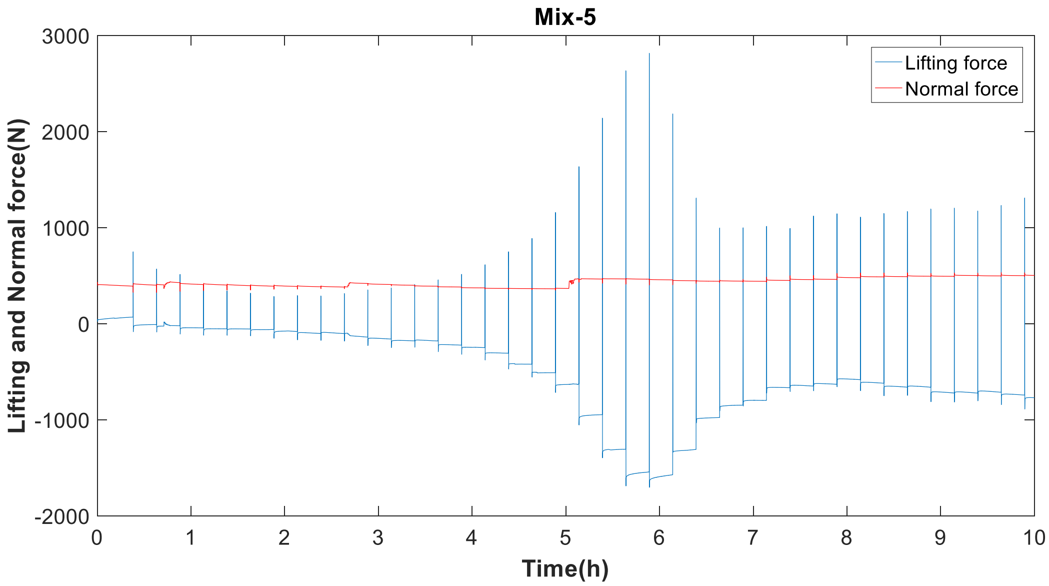


Figure 24 Lifting and Normal force mix 5

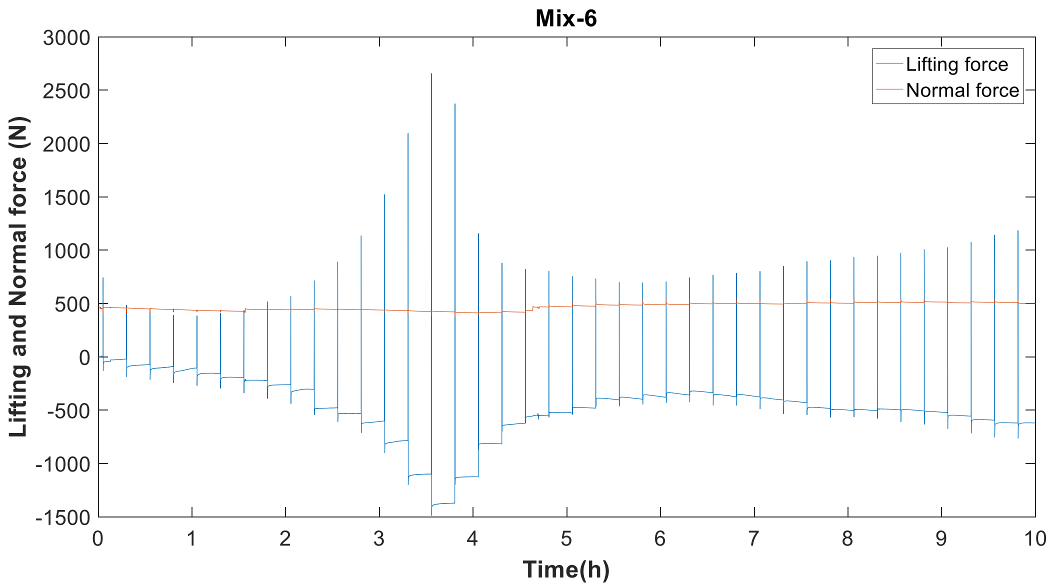


Figure 25 Lifting and Normal force mix 6

5.5. Pore pressure

The rate of pore water pressure for Mix-3 and Mix-5 of the concrete mix are shown in the figure below.

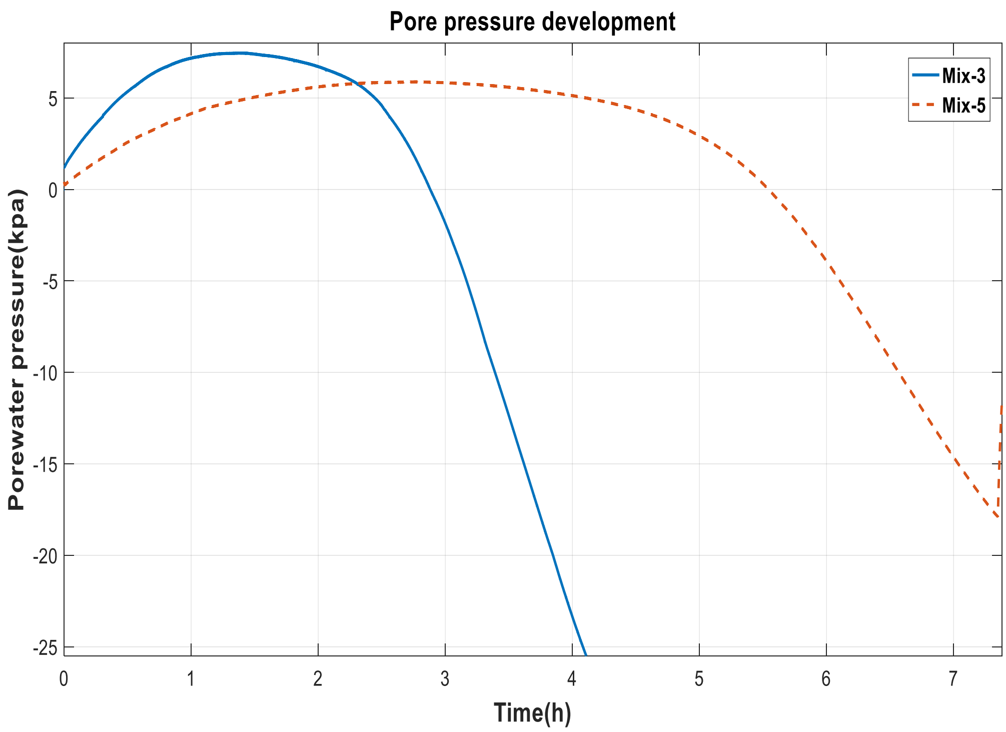


Figure 26 pore pressure development mix 3&5

The trend in the diagram shows that the rate of decreasing of the pore water pressure is reasonable. At first stage when the concrete is fresh, the graph shows positive pore pressure. This is mainly due to the liquid part of the concrete surrounded the solid particles, which are the main constituents for the contribution of frictional force between the panel and concrete. But after few hours the pore pressure starts to fall to negative pore pressure due to the hydration process. This is the general trend expected from the theory part.

According to the content of clinker and fly ash in the mix the rate of decreasing of pore water pressure in mix-3 and mix-5 differs as shown. As the main part of the thesis which is to focus how slipforming works affected in environmentally friendly concrete mix with reference to the normal amount of clinker content. It is shown the rate of decreasing of pore pressure, which is the main parameter on the effect of friction is higher in mix-3 with higher clinker amount and the setting time is shorter as well.

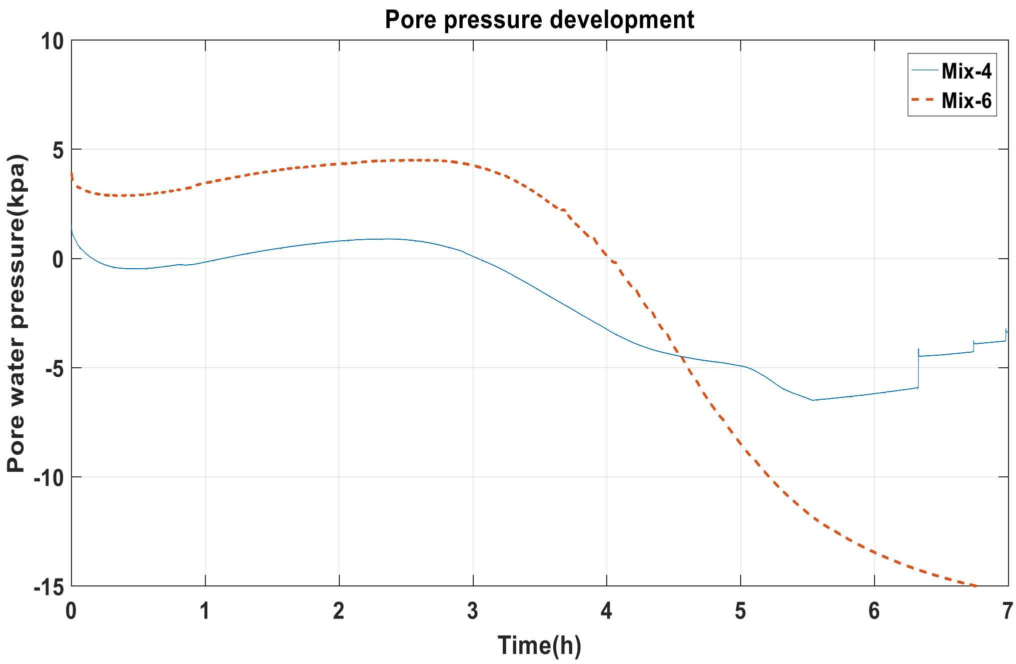


Figure 27 Pore pressure mix 4&6

In the above figure the rate of decreasing of negative pore water pressure is the higher in mix 6 (with lower amount of clinker) which is not reasonable. This is possibly due to the error occurred when calibrating the pore water measurement gauge in the water. But the pore pressure changed from positive to negative rate which indicates the setting time, is after 3 hours for mix 4 and after 4 hours for mix 6 which is reasonable according to the content of clinker.

The following figures show the relations between the lifting force, pore pressure and normal force.

It is shown that when the rate of decreasing of the pore pressure is higher, the need for lifting force starts to increase. The concrete hydration process is also starting at higher rate when the pore pressure becomes below zero. According to the litrature, in all the mixes, as shown in the diagrams below, the results are resonable.

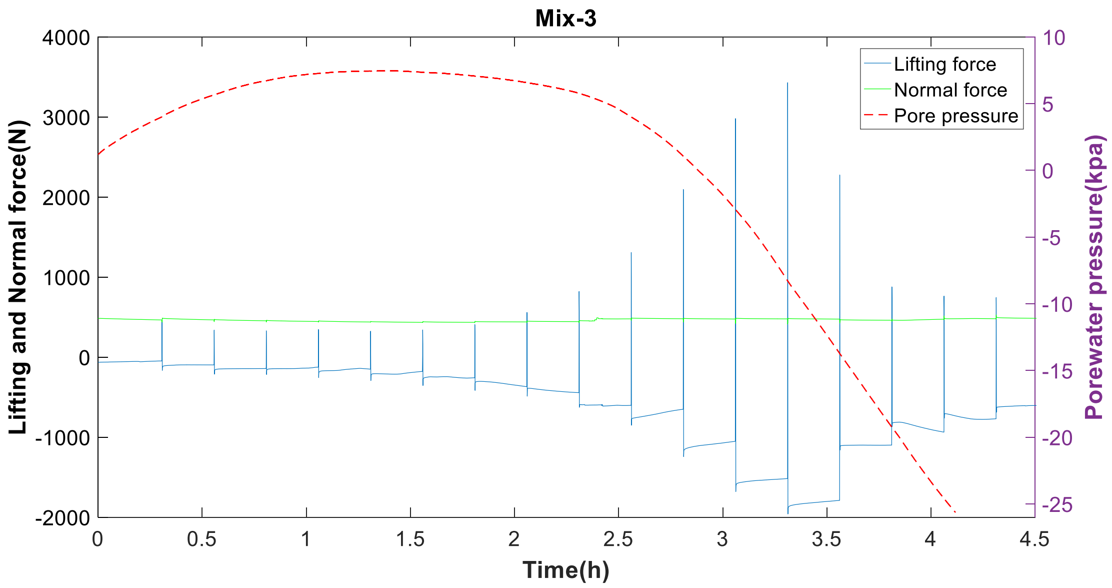


Figure 28 Normal, Lifting force and pore pressure mix 3

The normal force is maintained constant throughout the process by adjusting manually. Since the pressure exerted from the concrete varied as the hydration process continued up to final hardening process, the four sensors at the back of the slip rig was continuously monitored to keep constant normal force. In this experiment the normal force and lifting frequency were kept constant so that the difference in the lifting force was mainly the variation of the pore water pressure.

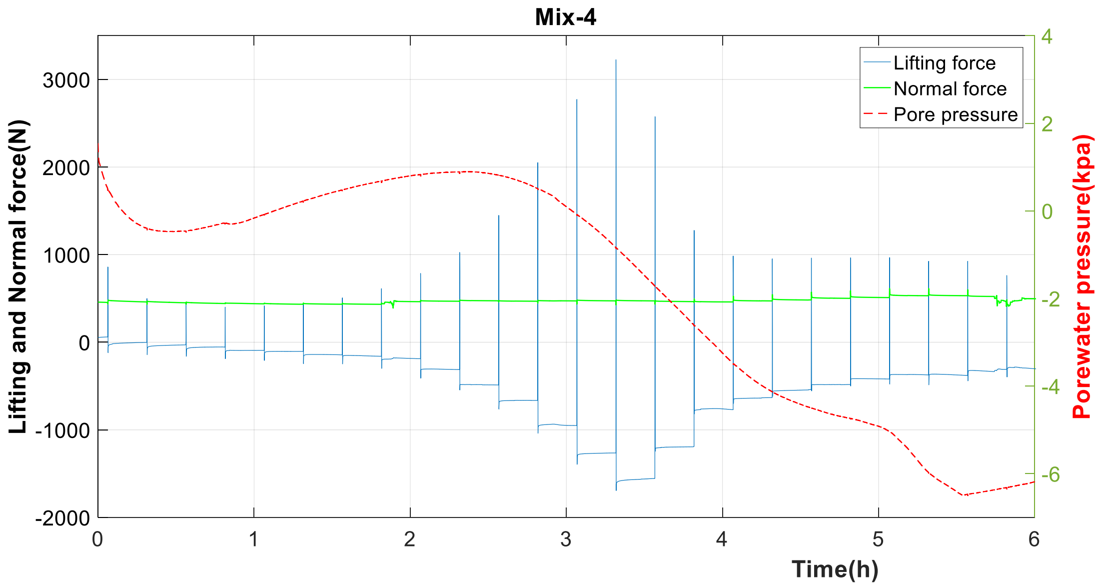


Figure 29 Normal, Lifting force and pore pressure mix 4

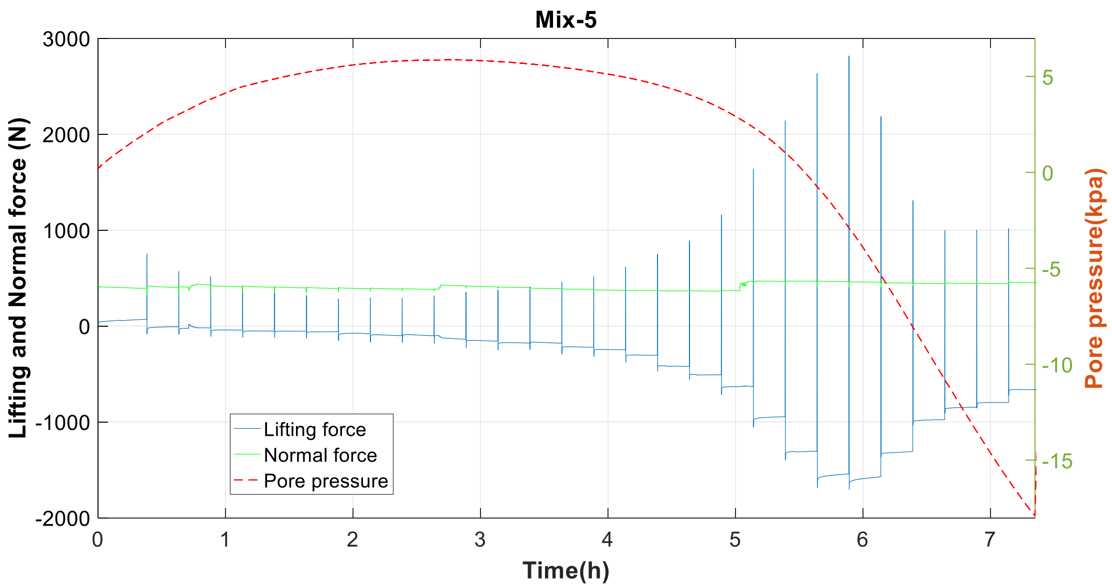


Figure 30 Normal, Lifting force and pore pressure mix 5

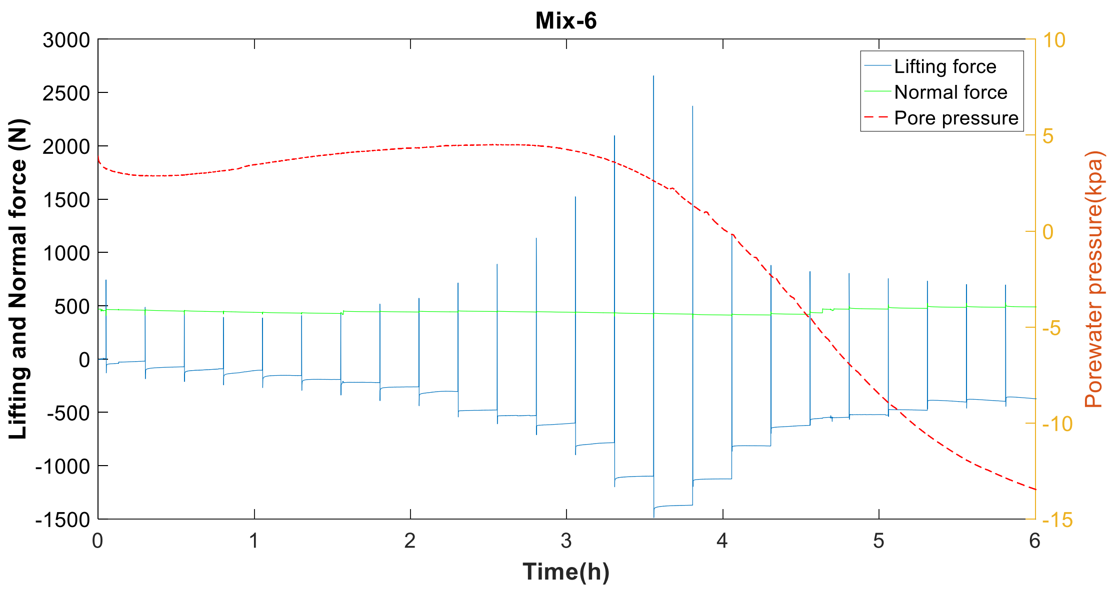


Figure 31 Normal, Lifting force and pore pressure mix 6

The following figures show the relation between temperature development, effective pressure, and pore pressure.

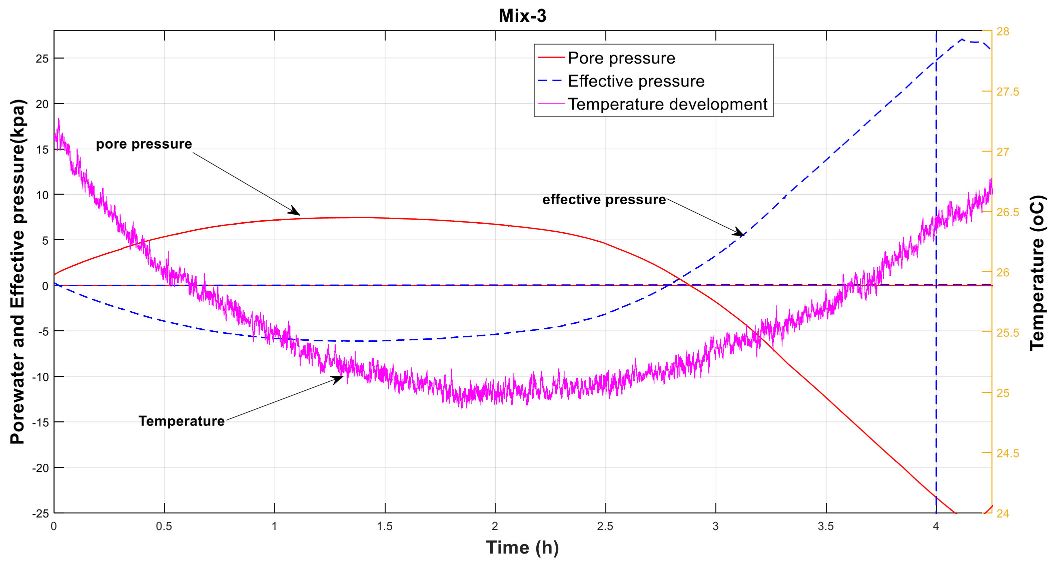


Figure 32 Pore pressure, effective pressure, normal pressure and temperature Mix 3

It is shown that when the pore pressure decreases and crosses zero towards negative pore pressure development, the temperature also rises from its dormant period. This clearly indicates, as per the lecture study, that the final setting time and regarded as the start of hardening phase. At this level the solid particles of the concrete become closer and the effective pressure starts to increase. The need for lifting power starts to increase to the maximum level.

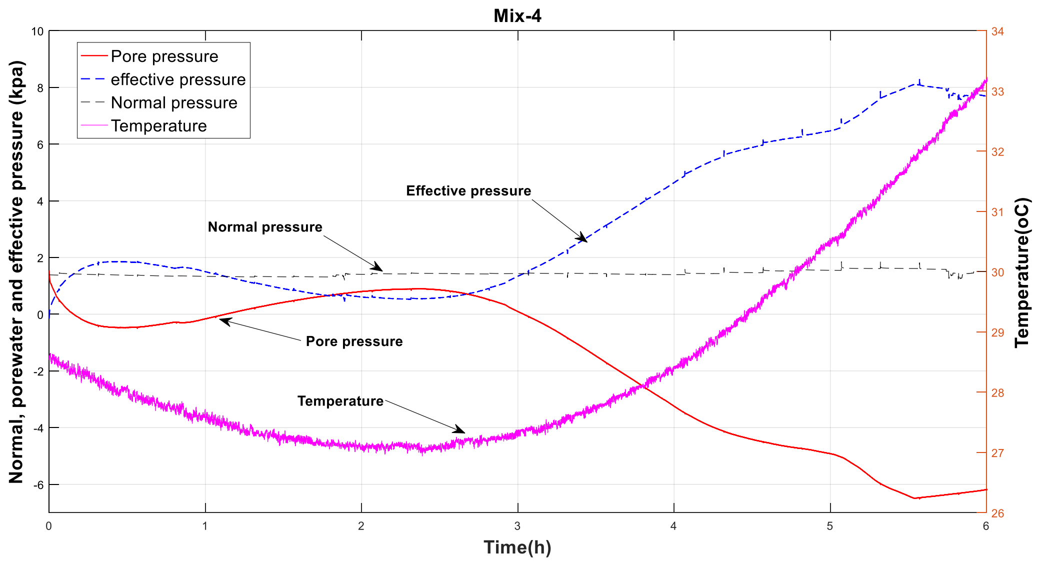


Figure 33 Pore pressure, effective pressure, normal pressure and temperature Mix 4

When we compare the concrete mixes used in the test process , the mixes with the same w/b ratio but different amount of clinker (mix 3 and 5), the mix with higher clinker reaches its final setting time earlier than with lower amount of clinker. This is obviously reasonable as the temperature development or heat development of concrete with high amount of clinker is higher. The same for mix 4 and 6, with mix 4 has higher amount of clinker.

It is also shown that in the graphs that concrete with nearly same amount of clinker but different w/b ratio (mix 3 ad 4), the final setting time differs. According to the lecture, the higher the w/b ratio the lower time of final setting time. In this case mix 3 (w/b =0.35) has the lower final setting time than that of mix 4 (w/b=0.30). the same result with mix 5 (w/b=0.35) and Mix6 (w/b=0.30).

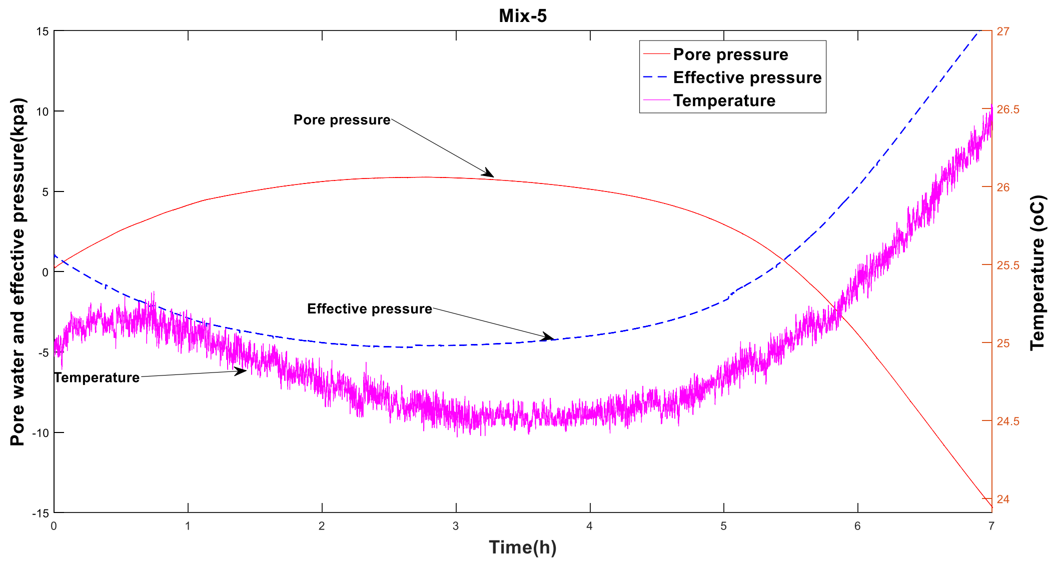


Figure 34 Pore pressure, effective pressure, normal pressure and temperature Mix 5

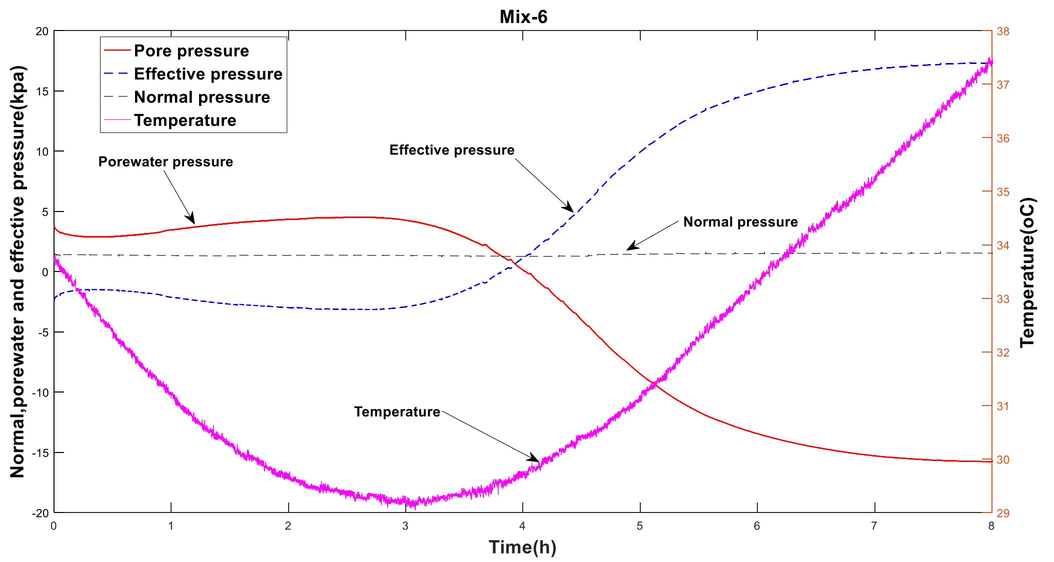


Figure 35 Pore pressure, effective pressure, normal pressure and temperature Mix 6

As per the above graphs of the pore pressure and effective pressure, the maximum lifting force of those concrete mix, with same w/b ratio but different amount of clinker and fly ash, shown in figure below.

The graph shows that the maximum lifting force reaches earlier in the mix with higher clinker and less fly ash added. This is reasonable as per the results shown above.

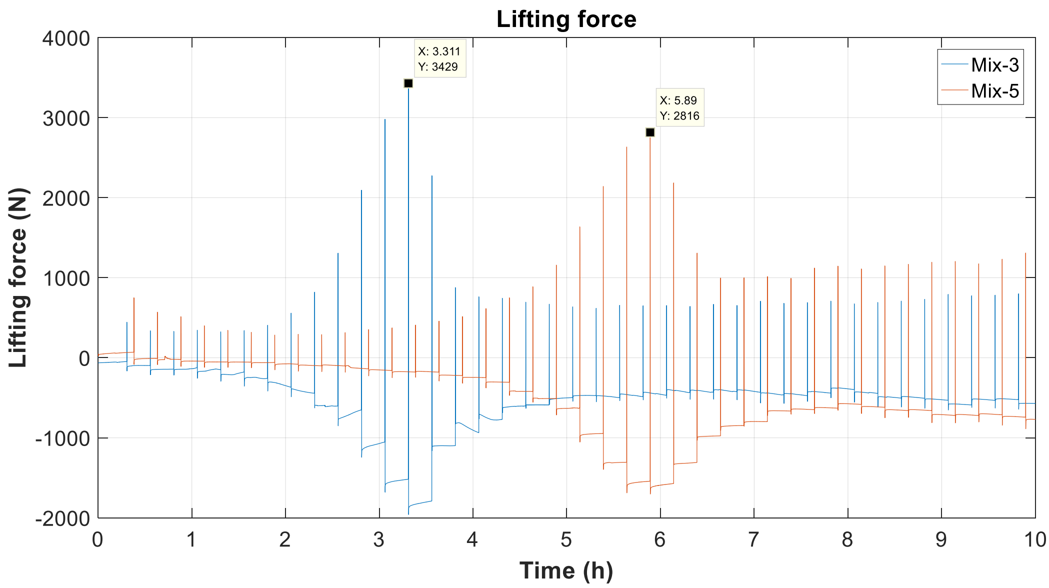


Figure 36 Lifting force mix 3 and 5

The same results shown for mix 4 and 6 with w/b ratio 0.35, except that the time for the maximum lifting force is closer in this case, which has no clear reason for this. But with more experiment and tests the reason might be clear. Unfortunately, due to the corona virus lock down it could not be done further studies in the university of Stavanger laboratory.

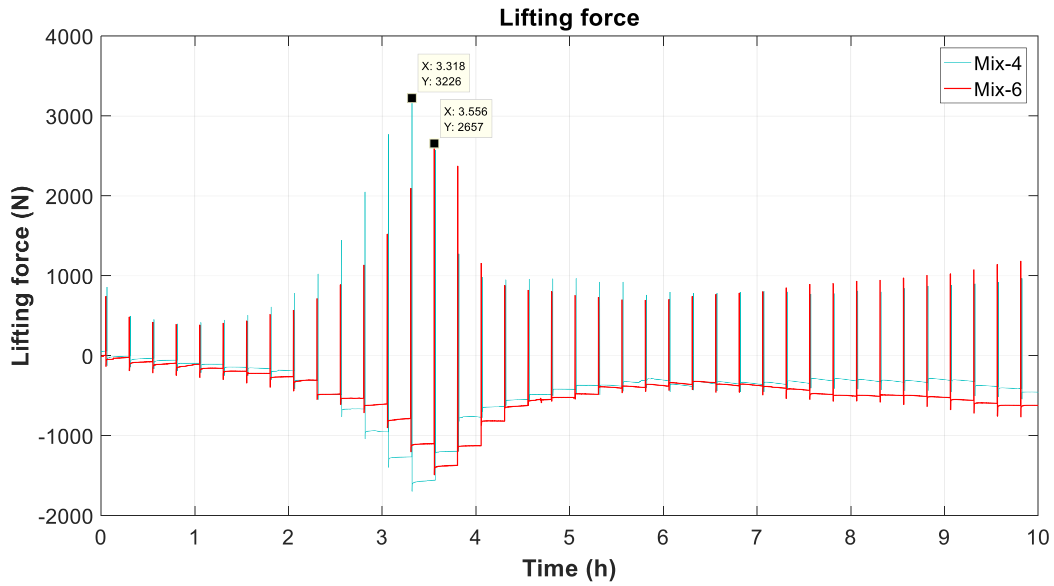


Figure 37 Lifting forces mix 4 and 6

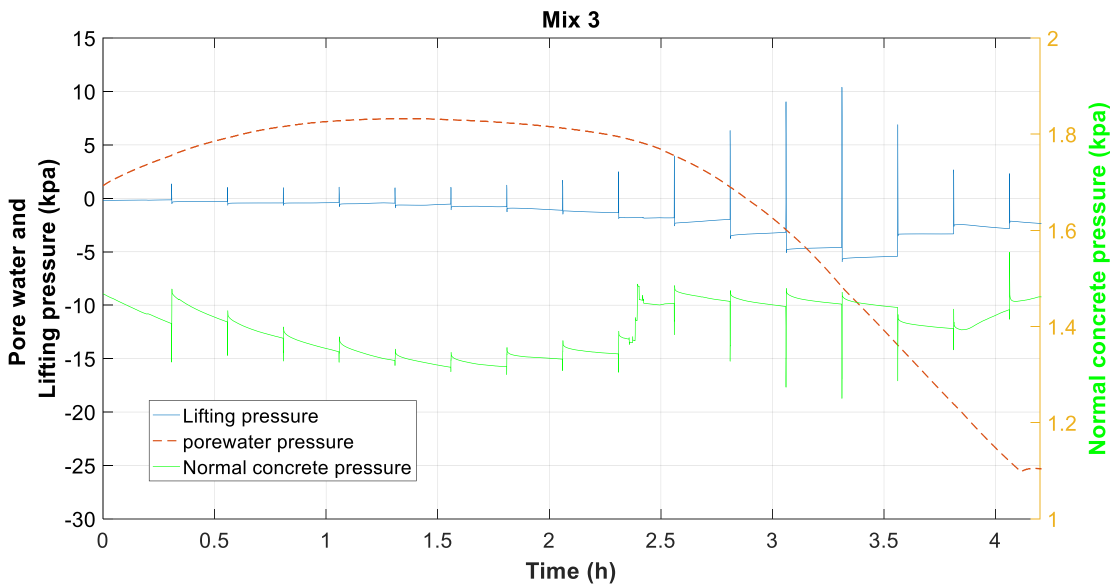


Figure 38 Pore pressure, normal and lifting pressure

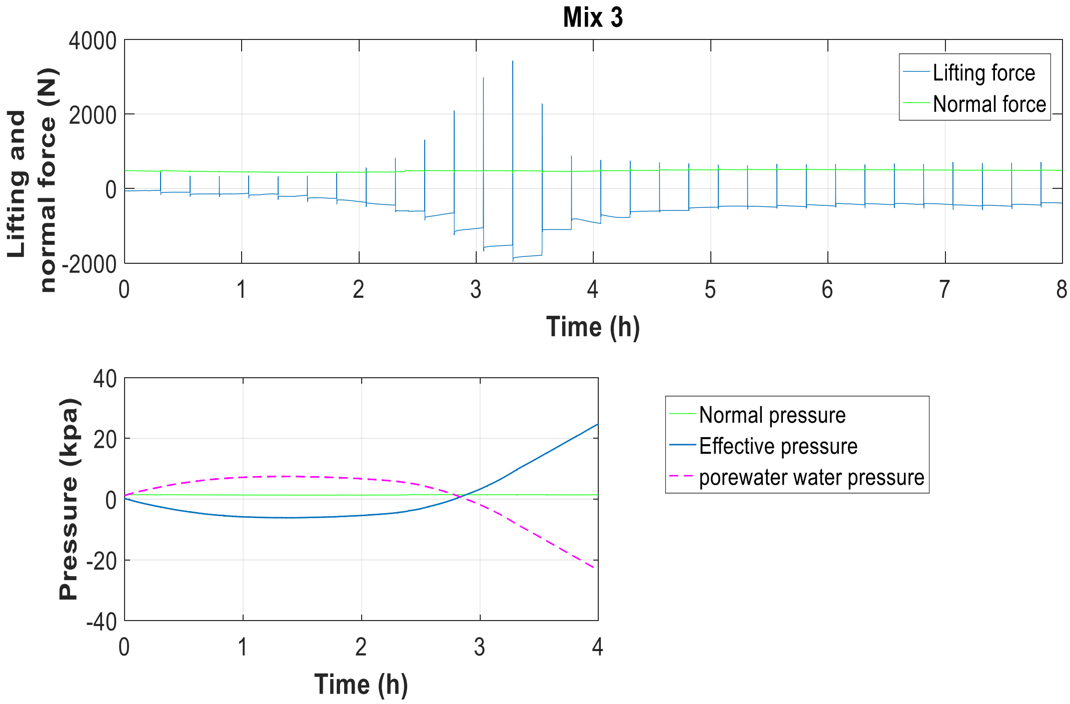
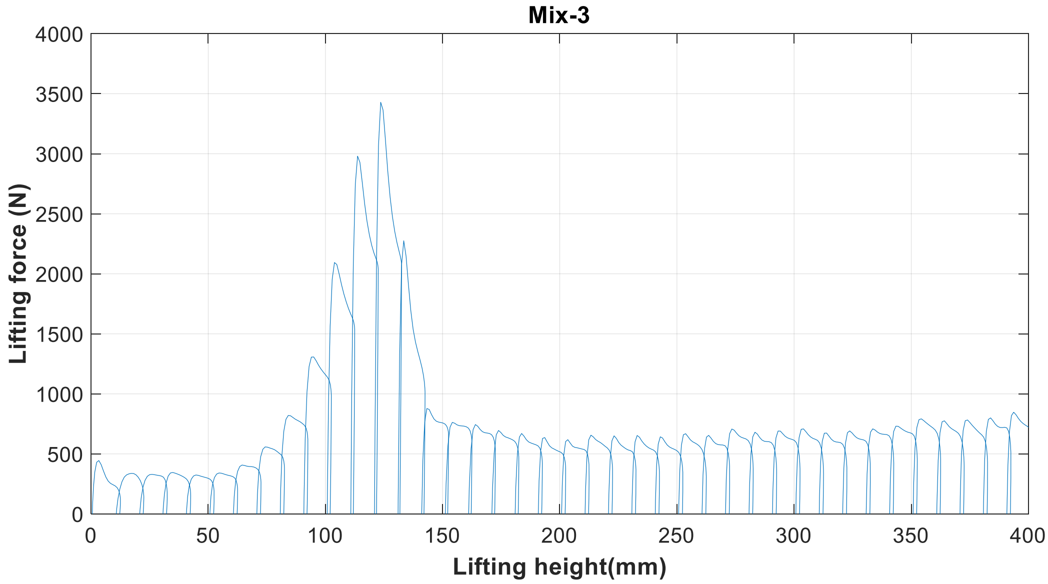


Figure 39 Maximumm lifting force with minimum pore pressure and maximum effective pressure

In the above figure, it can be shown that the time for minimum pore pressure and maximum lifting force occur at the same time. It also shows that the Lifting force is only affected by the change of effective pressure due to the difference in pore pressure while keeping the normal pressure constant.



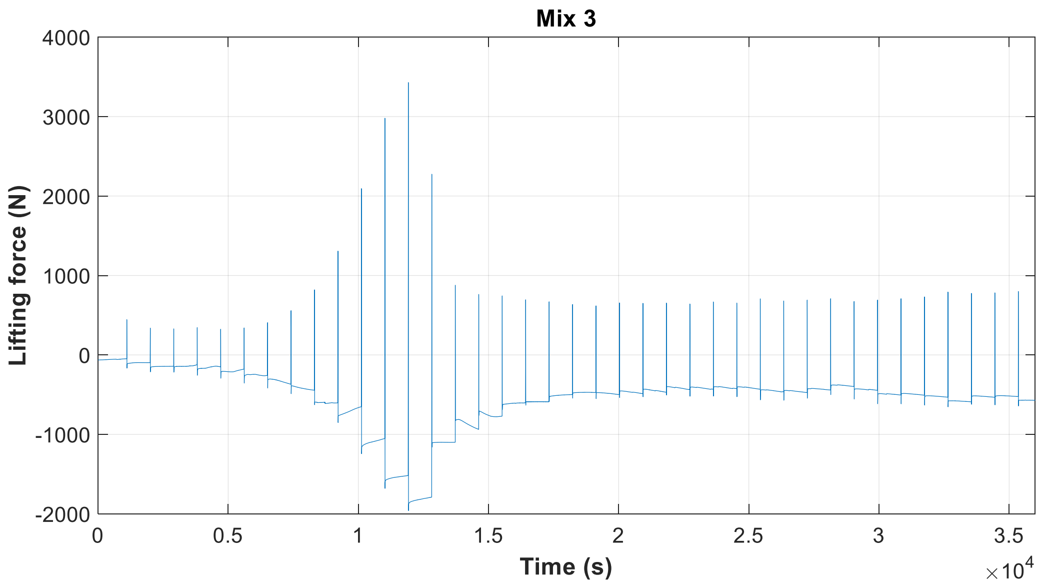


Figure 40 Lifting height and Lifting force

5.6. Surface damage

In general, no surface damages were observed on any of the samples. As mentioned in part a vibrator was used in all the mixes while casting to the slipform rig this is because of the consistency of the fresh concrete mix was not as expected. Therefore, it cannot be concluded that the surface is safe and sound. Some defects like formation of pores on the surface was observed.

Figure 41 Surface of the concrete

6. Conclusion

The purpose of this thesis is to determine the parameters affecting the frictional force that occurs between the slipform panel and environmentally friendly concrete mixes. The focus is to identify the influence of pore water pressure on the frictional force occurs between the slipform panel and the concrete. In addition, the effect of the frictional force to the surface damage also studied.

The relationship between the frictional force and porewater pressure with respect to the materials type, size and composition used in proportioning of the concrete mix, the chemical and mechanical behaviour of a fresh and hardened concrete, the temperature development and hydration process and the w/b ratio has been first studied to predict the interfacial behaviour between the slipform panel and the concrete.

Based on the results from the experiments, it can be seen that:

- The decreasing rate of pore water pressure is higher in the concrete mixes with normal anleggsement FA than the mixes with 20% clinker replacement with fly ash provided that the w/b ratio is the same (mix 3 and 5).
- The minimum pore water pressure reaches earlier stage in the mixes with normal anleggsement FA than the mixes with 20% clinker replacement with fly ash.
- The temperature evolution in the concrete mixes with normal anleggsement amount of clinker tends to change at earlier stage from the dormant period to the acceleration of the hydration reactions stage.
- The lifting force needed to overcome the frictional force reaches its maximum value at earlier stage in the concrete mix with normal anleggsement FA than the 20% clinker replacement with fly ash.

Based on the above results, it can be concluded that, the slipform rig is able to reproduce results using environmentally friendly concrete (20% clinker replacement with fly ash) with longer time to reach the maximum lifting force (frictional force) than the concrete with normal anleggsement FA cement but same w/b ratio. Therefore, in actual work, the lifting rate of the slipform would be lower when using environmentally friendly concrete mix.

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8. Appendix

Appendix 1 – Raw data obtained from the test rig for each mix of the first few seconds

Mix 3

Time(s)	Position (mm)	T1 (ºC)	T2 (ºC)	T3 (ºC)	Pore pressure (bar)	Tension wall (KN)	Right upper (N)	Right lower (N)	Left upper (N)	Left down(N)	Total upper (N)	Total lower (N)
0.0000	0.5129	27.1206	28.8385	106.0654	0.0121	0.0644	208.4450	787.3278	203.6908	738.8752	412.0958	1526.1634
0.2000	0.5153	27.1251	28.8167	106.0655	0.0121	0.0644	208.4434	787.3204	203.6958	738.8726	412.0991	1526.1535
0.4000	0.5160	27.1288	28.7936	106.0654	0.0121	0.0645	208.4426	787.3144	203.6984	738.8666	412.1010	1526.1414
0.6000	0.5149	27.1290	28.7790	106.0653	0.0121	0.0644	208.4440	787.3083	203.6951	738.8541	412.0991	1526.1228
0.8000	0.5129	27.1266	28.7764	106.0652	0.0121	0.0644	208.4451	787.3007	203.6868	738.8386	412.0919	1526.0997
1.0000	0.5110	27.1251	28.7806	106.0652	0.0121	0.0644	208.4461	787.2922	203.6775	738.8253	412.0835	1526.0779
1.2000	0.5098	27.1282	28.7845	106.0654	0.0121	0.0644	208.4467	787.2826	203.6724	738.8205	412.0791	1526.0635
1.4000	0.5094	27.1319	28.7852	106.0655	0.0121	0.0644	208.4462	787.2706	203.6732	738.8204	412.0794	1526.0515
1.6000	0.5100	27.1321	28.7802	106.0655	0.0121	0.0644	208.4463	787.2611	203.6753	738.8201	412.0815	1526.0416
1.8000	0.5110	27.1312	28.7747	106.0652	0.0121	0.0644	208.4424	787.2594	203.6749	738.8190	412.0773	1526.0388
2.0000	0.5111	27.1308	28.7768	106.0650	0.0121	0.0644	208.4351	787.2618	203.6717	738.8188	412.0667	1526.0410
2.2000	0.5108	27.1260	28.7810	106.0650	0.0121	0.0644	208.4280	787.2598	203.6709	738.8151	412.0589	1526.0354
2.4000	0.5096	27.1128	28.7866	106.0652	0.0121	0.0644	208.4209	787.2502	203.6705	738.8043	412.0514	1526.0149
2.6000	0.5080	27.1044	28.7924	106.0654	0.0121	0.0644	208.4138	787.2357	203.6683	738.7907	412.0421	1525.9868
2.8000	0.5068	27.1046	28.7974	106.0655	0.0121	0.0643	208.4100	787.2200	203.6639	738.7825	412.0339	1525.9629
3.0000	0.5066	27.1083	28.8043	106.0654	0.0121	0.0643	208.4116	787.2034	203.6608	738.7790	412.0324	1525.9428
3.2000	0.5073	27.1152	28.8066	106.0653	0.0121	0.0643	208.4148	787.1897	203.6579	738.7776	412.0326	1525.9278
3.4000	0.5080	27.1208	28.8051	106.0651	0.0121	0.0643	208.4146	787.1798	203.6525	738.7756	412.0271	1525.9158
3.6000	0.5082	27.1248	28.8046	106.0650	0.0121	0.0643	208.4131	787.1722	203.6455	738.7689	412.0186	1525.9015
3.8000	0.5084	27.1273	28.8118	106.0648	0.0121	0.0643	208.4169	787.1685	203.6404	738.7599	412.0172	1525.8888
4.0000	0.5090	27.1239	28.8197	106.0647	0.0121	0.0643	208.4222	787.1663	203.6406	738.7549	412.0228	1525.8817
4.2000	0.5090	27.1141	28.8271	106.0646	0.0121	0.0643	208.4232	787.1627	203.6429	738.7516	412.0261	1525.8747
4.4000	0.5082	27.1057	28.8341	106.0646	0.0122	0.0643	208.4208	787.1527	203.6433	738.7446	412.0240	1525.8577
4.6000	0.5078	27.1052	28.8332	106.0646	0.0122	0.0643	208.4160	787.1393	203.6419	738.7320	412.0179	1525.8318
4.8000	0.5077	27.1124	28.8219	106.0648	0.0122	0.0643	208.4100	787.1260	203.6386	738.7166	412.0086	1525.8030
5.0000	0.5079	27.1216	28.8108	106.0649	0.0122	0.0643	208.4055	787.1159	203.6353	738.7106	412.0007	1525.7869
5.2000	0.5079	27.1241	28.8092	106.0649	0.0121	0.0643	208.4043	787.1065	203.6326	738.7136	411.9969	1525.7805
5.4000	0.5078	27.1203	28.8112	106.0649	0.0122	0.0642	208.4009	787.0984	203.6305	738.7131	411.9914	1525.7719
5.6000	0.5081	27.1180	28.8077	106.0650	0.0122	0.0642	208.3918	787.0916	203.6302	738.7064	411.9820	1525.7584
5.8000	0.5085	27.1148	28.7994	106.0652	0.0122	0.0642	208.3785	787.0847	203.6297	738.6991	411.9681	1525.7442
6.0000	0.5080	27.1115	28.7847	106.0652	0.0122	0.0643	208.3662	787.0752	203.6285	738.6924	411.9547	1525.7280
6.2000	0.5068	27.1047	28.7752	106.0653	0.0122	0.0643	208.3634	787.0699	203.6269	738.6886	411.9503	1525.7190
6.4000	0.5064	27.0936	28.7784	106.0654	0.0122	0.0643	208.3699	787.0726	203.6266	738.6909	411.9565	1525.7239
6.6000	0.5074	27.0874	28.7890	106.0654	0.0122	0.0643	208.3811	787.0768	203.6257	738.6965	411.9668	1525.7337
6.8000	0.5087	27.0900	28.7905	106.0653	0.0122	0.0643	208.3914	787.0802	203.6236	738.7015	411.9750	1525.7421
7.0000	0.5097	27.1011	28.7801	106.0653	0.0122	0.0642	208.3968	787.0837	203.6245	738.7057	411.9813	1525.7498
7.2000	0.5104	27.1142	28.7691	106.0654	0.0122	0.0643	208.3990	787.0870	203.6259	738.7061	411.9849	1525.7535
7.4000	0.5109	27.1194	28.7647	106.0655	0.0122	0.0643	208.3974	787.0863	203.6262	738.7031	411.9835	1525.7498
7.6000	0.5107	27.1179	28.7734	106.0655	0.0122	0.0643	208.3944	787.0810	203.6257	738.7017	411.9801	1525.7431
7.8000	0.5101	27.1164	28.7903	106.0654	0.0122	0.0643	208.3941	787.0728	203.6224	738.6983	411.9764	1525.7315
8.0000	0.5097	27.1181	28.8049	106.0652	0.0122	0.0642	208.3926	787.0616	203.6162	738.6901	411.9688	1525.7121
8.2000	0.5096	27.1222	28.8082	106.0650	0.0122	0.0642	208.3872	787.0486	203.6085	738.6807	411.9557	1525.6898
8.4000	0.5097	27.1239	28.8006	106.0649	0.0122	0.0642	208.3772	787.0329	203.6019	738.6730	411.9390	1525.6663
8.6000	0.5101	27.1229	28.7845	106.0649	0.0122	0.0642	208.3706	787.0214	203.5971	738.6647	411.9276	1525.6465
8.8000	0.5103	27.1233	28.7677	106.0651	0.0122	0.0643	208.3700	787.0148	203.5950	738.6595	411.9250	1525.6347
9.0000	0.5102	27.1250	28.7583	106.0652	0.0122	0.0643	208.3736	787.0107	203.5951	738.6622	411.9287	1525.6333
9.2000	0.5103	27.1254	28.7539	106.0652	0.0122	0.0643	208.3773	787.0063	203.5966	738.6674	411.9338	1525.6341
9.4000	0.5104	27.1239	28.7525	106.0651	0.0122	0.0642	208.3764	786.9979	203.5938	738.6651	411.9301	1525.6234
9.6000	0.5100	27.1194	28.7523	106.0650	0.0122	0.0642	208.3710	786.9890	203.5890	738.6572	411.9200	1525.6066
9.8000	0.5099	27.1157	28.7470	106.0649	0.0122	0.0643	208.3645	786.9809	203.5859	738.6464	411.9104	1525.5877
10.0000	0.5104	27.1120	28.7432	106.0649	0.0122	0.0642	208.3579	786.9693	203.5832	738.6346	411.9010	1525.5643
10.2000	0.5115	27.1095	28.7477	106.0649	0.0122	0.0642	208.3512	786.9572	203.5818	738.6253	411.8929	1525.5429
10.4000	0.5124	27.1108	28.7584	106.0650	0.0122	0.0641	208.3464	786.9487	203.5840	738.6183	411.8904	1525.5275
10.6000	0.5130	27.1157	28.7699	106.0652	0.0123	0.0641	208.3433	786.9432	203.5833	738.6111	411.8865	1525.5147
10.8000	0.5130	27.1201	28.7802	106.0654	0.0123	0.0641	208.3446	786.9379	203.5789	738.6038	411.8834	1525.5021
11.0000	0.5124	27.1239	28.7847	106.0655	0.0123	0.0641	208.3486	786.9307	203.5765	738.5995	411.8851	1525.4906
11.2000	0.5114	27.1272	28.7932	106.0655	0.0123	0.0642	208.3485	786.9175	203.5734	738.5972	411.8818	1525.4751
11.4000	0.5107	27.1279	28.8095	106.0654	0.0123	0.0642	208.3449	786.9005	203.5668	738.5927	411.8717	1525.4536
11.6000	0.5107	27.1273	28.8238	106.0653	0.0123	0.0641	208.3434	786.8885	203.5600	738.5882	411.8634	1525.4372
11.8000	0.5116	27.1244	28.8305	106.0654	0.0122	0.0641	208.3450	786.8846	203.5547	738.5847	411.8597	1525.4297
12.0000	0.5131	27.1211	28.8245	106.0655	0.0123	0.0641	208.3472	786.8831	203.5549	738.5823	411.8620	1525.4258
12.2000	0.5143	27.1190	28.8039	106.0654	0.0123	0.0641	208.3457	786.8838	203.5611	738.5786	411.8667	1525.4228

Mix 4

Time(s)	Position (mm)	T1 (ºC)	T2 (ºC)	T3 (ºC)	Pore pressure (bar)	Tension wall (KN)	Right upper (N)	Right lower (N)	Left upper (N)	Left down(N)	Total upper (N)	Total lower (N)
0	0.505262	27.99343	28.56352	106.0593	0.0154447	-0.055427	229.3818	719.6583	185.3824	698.5187	414.7242	1418.137
0.2	0.504389	28.00097	28.5565	106.0593	0.0153752	-0.055463	229.3764	719.6462	185.3787	698.5066	414.7151	1418.113
0.4	0.503446	28.00427	28.55512	106.0593	0.0153021	-0.055462	229.3706	719.6392	185.3759	698.4973	414.7065	1418.097
0.6	0.502557	28.01248	28.55707	106.0593	0.0152218	-0.055454	229.3639	719.6309	185.3744	698.4926	414.6983	1418.084
0.8	0.502084	28.02964	28.55556	106.0592	0.0151427	-0.055467	229.3569	719.6181	185.3745	698.4904	414.6913	1418.069
1	0.501928	28.04725	28.55205	106.059	0.0150702	-0.055493	229.3508	719.6	185.3698	698.4867	414.6806	1418.047
1.2	0.502307	28.05282	28.55508	106.059	0.0149961	-0.055513	229.3483	719.5851	185.3593	698.4835	414.6676	1418.029
1.4	0.502747	28.04498	28.5642	106.059	0.0149199	-0.055533	229.3468	719.5756	185.3502	698.4798	414.6569	1418.016
1.6	0.503173	28.03224	28.56959	106.0592	0.014845	-0.055566	229.346	719.5677	185.3444	698.4748	414.6504	1418.003
1.8	0.504396	28.0235	28.56965	106.0593	0.0147812	-0.055611	229.345	719.556	185.3409	698.4677	414.6458	1417.984
2	0.505451	28.02253	28.56587	106.0593	0.0147228	-0.055631	229.3421	719.5458	185.3436	698.4579	414.6457	1417.964
2.2	0.505644	28.02289	28.5622	106.0592	0.0146572	-0.055602	229.3411	719.5432	185.3493	698.45	414.6504	1417.954
2.4	0.505885	28.01637	28.56427	106.0591	0.0145824	-0.055553	229.3421	719.5423	185.3507	698.4468	414.6528	1417.95
2.6	0.50667	28.00853	28.57245	106.059	0.0145128	-0.055515	229.3412	719.5386	185.3531	698.4459	414.6543	1417.945
2.8	0.507091	28.00256	28.58109	106.0592	0.0144494	-0.055502	229.3383	719.5323	185.3574	698.4394	414.6557	1417.932
3	0.506962	28.00164	28.59444	106.0592	0.0143853	-0.055494	229.3329	719.5254	185.3592	698.4276	414.652	1417.913
3.2	0.506677	28.01053	28.601	106.0593	0.0143163	-0.055511	229.3291	719.5166	185.3547	698.4191	414.6437	1417.896
3.4	0.506102	28.02766	28.5987	106.0593	0.0142511	-0.055535	229.3309	719.5104	185.3467	698.4158	414.6376	1417.887
3.6	0.505089	28.04532	28.59346	106.0593	0.0141944	-0.055545	229.332	719.5089	185.3387	698.4119	414.6307	1417.881
3.8	0.503787	28.05407	28.58932	106.0592	0.0141371	-0.05552	229.3302	719.5108	185.3323	698.4062	414.6225	1417.877
4	0.502926	28.05088	28.58466	106.059	0.0140785	-0.055502	229.326	719.506	185.3267	698.4003	414.6126	1417.867
4.2	0.502814	28.04451	28.57211	106.059	0.0140283	-0.055536	229.3188	719.4932	185.322	698.3916	414.6008	1417.845
4.4	0.503228	28.03075	28.56149	106.0589	0.0139996	-0.055611	229.3104	719.4734	185.3143	698.3788	414.5847	1417.813
4.6	0.503543	28.01172	28.55698	106.0589	0.0139742	-0.055683	229.3048	719.4554	185.302	698.3641	414.5668	1417.78
4.8	0.503441	28.00447	28.55597	106.059	0.0139327	-0.055719	229.3044	719.445	185.2958	698.3546	414.5602	1417.76
5	0.503874	28.00838	28.5555	106.059	0.0138808	-0.055729	229.3062	719.4392	185.2967	698.3497	414.5629	1417.749
5.2	0.50462	28.01336	28.55371	106.0591	0.0138307	-0.055717	229.3063	719.4355	185.3005	698.3455	414.5667	1417.741
5.4	0.504764	28.01695	28.54789	106.0592	0.0137826	-0.055701	229.3022	719.4285	185.3013	698.3407	414.5635	1417.73
5.6	0.504197	28.01732	28.54033	106.0593	0.0137283	-0.055685	229.2998	719.4189	185.2993	698.3339	414.5591	1417.713
5.8	0.503268	28.01613	28.53429	106.0593	0.0136691	-0.055665	229.2999	719.4099	185.2973	698.3262	414.5573	1417.697
6	0.502656	28.01095	28.53416	106.0593	0.0136234	-0.055672	229.3009	719.3967	185.2951	698.317	414.5559	1417.674
6.2	0.502948	28.01138	28.53877	106.0593	0.0135892	-0.05568	229.3038	719.3839	185.2946	698.3107	414.5584	1417.655
6.4	0.503735	28.01934	28.5446	106.0593	0.0135547	-0.055685	229.305	719.3741	185.2928	698.307	414.5578	1417.642
6.6	0.504013	28.02665	28.54626	106.0593	0.0135132	-0.055682	229.3034	719.3676	185.2891	698.3047	414.5525	1417.633
6.8	0.503849	28.03276	28.54495	106.0592	0.0134602	-0.055654	229.3024	719.3672	185.2906	698.3026	414.553	1417.63
7	0.503872	28.03296	28.54309	106.0591	0.0134058	-0.055622	229.3006	719.368	185.2948	698.2991	414.5553	1417.628
7.2	0.503772	28.02646	28.54558	106.0592	0.013355	-0.055612	229.2965	719.3645	185.2952	698.2905	414.5516	1417.615
7.4	0.503347	28.01531	28.54918	106.0592	0.0133104	-0.055625	229.288	719.3538	185.2892	698.2798	414.5371	1417.594
7.6	0.503364	28.00815	28.55444	106.0593	0.0132685	-0.055643	229.2779	719.3416	185.2802	698.2733	414.518	1417.575
7.8	0.504217	28.01232	28.56323	106.0593	0.0132316	-0.055664	229.27	719.3317	185.2708	698.2703	414.5008	1417.562
8	0.504959	28.02756	28.57199	106.0593	0.0131925	-0.055685	229.2668	719.321	185.2628	698.2714	414.4896	1417.553
8.2	0.505371	28.04758	28.57965	106.0593	0.013134	-0.055662	229.274	719.3171	185.2648	698.2766	414.4987	1417.554
8.4	0.506671	28.06455	28.58997	106.0593	0.0130691	-0.055638	229.2838	719.319	185.2711	698.2751	414.5149	1417.555
8.6	0.508121	28.07525	28.5995	106.0593	0.0130232	-0.055673	229.2872	719.3146	185.2703	698.2648	414.5175	1417.54
8.8	0.508122	28.07801	28.60568	106.0593	0.0129916	-0.055735	229.2848	719.3029	185.2617	698.2516	414.5064	1417.515
9	0.506783	28.07455	28.60483	106.0593	0.0129589	-0.0558	229.2797	719.2856	185.2525	698.2376	414.4922	1417.484
9.2	0.505188	28.06321	28.5983	106.0594	0.0129228	-0.055858	229.2772	719.2715	185.2436	698.2251	414.4807	1417.457
9.4	0.503886	28.04462	28.59436	106.0594	0.0128872	-0.055859	229.2772	719.2668	185.2389	698.2209	414.4761	1417.448
9.6	0.50281	28.03442	28.59337	106.0594	0.0128552	-0.055789	229.2721	719.2654	185.2404	698.2247	414.4724	1417.451
9.8	0.501716	28.03006	28.59735	106.0593	0.012825	-0.055743	229.2618	719.2558	185.2388	698.2261	414.4606	1417.442
10	0.500887	28.02892	28.60439	106.0592	0.0127893	-0.055758	229.2539	719.2401	185.2381	698.2241	414.452	1417.425
10.2	0.500863	28.0287	28.60907	106.0592	0.0127379	-0.05577	229.2533	719.2303	185.246	698.221	414.4592	1417.412
10.4	0.50101	28.03304	28.6114	106.0592	0.012687	-0.055755	229.2549	719.2266	185.2566	698.2169	414.4715	1417.404
10.6	0.500587	28.04383	28.61454	106.0592	0.0126454	-0.055718	229.2561	719.2271	185.264	698.2112	414.48	1417.399
10.8	0.499501	28.06365	28.61479	106.0592	0.0126063	-0.055682	229.2539	719.2259	185.2682	698.2035	414.4821	1417.39
11	0.498158	28.08729	28.61006	106.0592	0.0125674	-0.055677	229.2501	719.219	185.2655	698.1933	414.4756	1417.373
11.2	0.49733	28.10097	28.60425	106.0591	0.0125311	-0.055713	229.2491	719.2128	185.2558	698.1816	414.4648	1417.355
11.4	0.497824	28.108	28.60091	106.059	0.0124997	-0.055752	229.2513	719.2082	185.242	698.1693	414.4532	1417.338
11.6	0.499263	28.11336	28.60375	106.0591	0.0124619	-0.055754	229.2563	719.203	185.233	698.163	414.4492	1417.326
11.8	0.500636	28.10807	28.61412	106.0592	0.0124128	-0.05573	229.2621	719.1984	185.2343	698.1635	414.4564	1417.322

Mix 5

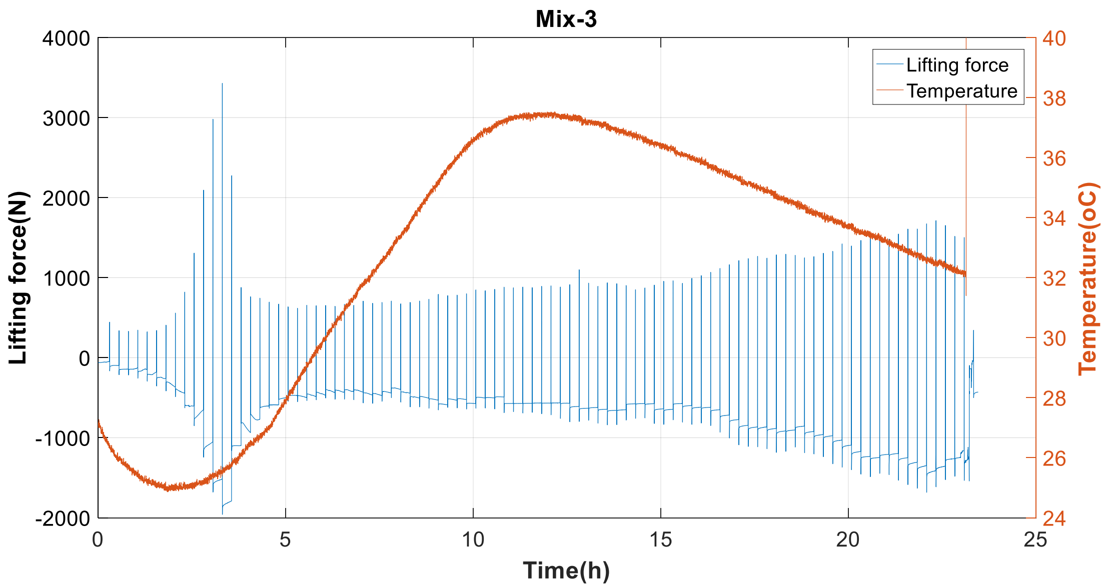
Time(s)	Position (mm)	T1 (ºC)	T2 (ºC)	T3 (ºC)	Pore pressure (bar)	Tension wall (KN)	Right upper (N)	Right lower (N)	Left upper (N)	Left down(N)	Total upper (N)	Total lower (N)
0	0.498339	24.94109	25.51316	106.0635	0.0041928	-0.0465	58.47272	817.2905	255.6575	549.816	314.0902	1367.067
0.2	0.499326	24.92777	25.50812	106.0635	0.0041456	-0.04642	58.47583	817.3033	255.6647	549.8179	314.1005	1367.082
0.4	0.500315	24.93118	25.51473	106.0634	0.0041148	-0.04638	58.4758	817.3148	255.667	549.8176	314.1028	1367.093
0.6	0.500797	24.94724	25.53052	106.0633	0.0040811	-0.04641	58.47112	817.3138	255.6598	549.8125	314.0909	1367.087
0.8	0.500879	24.96478	25.55119	106.0632	0.0040437	-0.04647	58.46679	817.3004	255.6492	549.8054	314.0759	1367.066
1	0.500879	24.97419	25.57217	106.0633	0.0040071	-0.04652	58.46622	817.2861	255.6457	549.7997	314.0718	1367.046
1.2	0.500989	24.97264	25.58941	106.0634	0.0039714	-0.04654	58.46707	817.2763	255.6475	549.7952	314.0745	1367.032
1.4	0.501248	24.96823	25.59971	106.0634	0.0039309	-0.04655	58.46567	817.2686	255.6469	549.7927	314.0725	1367.022
1.6	0.501546	24.95587	25.60031	106.0633	0.0038889	-0.04656	58.46575	817.2678	255.6439	549.7938	314.0697	1367.022
1.8	0.501667	24.94111	25.59144	106.0632	0.0038552	-0.04657	58.47104	817.27	255.6409	549.7961	314.0719	1367.027
2	0.501357	24.92826	25.57224	106.0631	0.0038208	-0.04657	58.47499	817.2731	255.636	549.7946	314.0709	1367.028
2.2	0.500934	24.91992	25.54593	106.0631	0.0037757	-0.04658	58.47335	817.2739	255.6292	549.7876	314.0625	1367.022
2.4	0.50111	24.91481	25.52716	106.0631	0.0037322	-0.04658	58.47181	817.2696	255.6241	549.7753	314.0559	1367.005
2.6	0.502134	24.91109	25.53257	106.0631	0.0036961	-0.04658	58.47256	817.2642	255.6221	549.7614	314.0547	1366.986
2.8	0.50356	24.91342	25.55698	106.0632	0.0036588	-0.04656	58.47817	817.2607	255.6234	549.7558	314.0616	1366.977
3	0.503915	24.92151	25.5832	106.0634	0.0036229	-0.04654	58.48457	817.2594	255.6255	549.7544	314.07	1366.974
3.2	0.502916	24.93431	25.59384	106.0636	0.0035862	-0.04654	58.48807	817.2631	255.6289	549.7526	314.0769	1366.976
3.4	0.501671	24.94337	25.59179	106.0637	0.0035562	-0.04655	58.48327	817.2653	255.633	549.7516	314.0762	1366.977
3.6	0.500669	24.94887	25.58739	106.0637	0.0035286	-0.04658	58.4716	817.2609	255.6337	549.7498	314.0653	1366.971
3.8	0.499865	24.95252	25.5836	106.0635	0.0034966	-0.04661	58.46152	817.2484	255.6294	549.7473	314.0509	1366.956
4	0.499085	24.94941	25.58354	106.0633	0.0034637	-0.04664	58.45742	817.2377	255.6271	549.7424	314.0445	1366.941
4.2	0.49862	24.94421	25.58678	106.0631	0.0034353	-0.04667	58.45775	817.2325	255.6266	549.7355	314.0443	1366.928
4.4	0.498456	24.94072	25.59411	106.0632	0.0034104	-0.04667	58.46054	817.2285	255.6252	549.7305	314.0457	1366.919
4.6	0.498121	24.94065	25.6026	106.0634	0.0033813	-0.04666	58.46385	817.2225	255.622	549.7257	314.0458	1366.909
4.8	0.497801	24.94343	25.61074	106.0634	0.0033509	-0.04668	58.46705	817.2139	255.6152	549.7166	314.0422	1366.891
5	0.497853	24.95025	25.61678	106.0634	0.0033242	-0.04671	58.46618	817.2041	255.6078	549.7053	314.0339	1366.87
5.2	0.498487	24.96476	25.61891	106.0634	0.0032946	-0.04672	58.46469	817.1991	255.6048	549.6971	314.0294	1366.857
5.4	0.499353	24.98468	25.61636	106.0633	0.0032619	-0.04669	58.46634	817.2023	255.6055	549.6942	314.0318	1366.857
5.6	0.500977	24.99864	25.60759	106.0632	0.0032321	-0.04667	58.46884	817.2047	255.605	549.6897	314.0338	1366.855
5.8	0.503024	25.00352	25.59555	106.0631	0.0032097	-0.04668	58.46667	817.2036	255.6027	549.6801	314.0293	1366.844
6	0.505031	25.0056	25.59019	106.0631	0.0031913	-0.04672	58.45979	817.2057	255.6042	549.6697	314.024	1366.836
6.2	0.505376	25.00465	25.59123	106.0631	0.0031605	-0.04677	58.45372	817.2137	255.6064	549.6652	314.02	1366.839
6.4	0.504146	24.99643	25.59428	106.0632	0.0031194	-0.0468	58.45254	817.2211	255.609	549.6658	314.0215	1366.847
6.6	0.502168	24.99061	25.58899	106.0634	0.0030895	-0.04681	58.45388	817.2189	255.6098	549.6653	314.0237	1366.845
6.8	0.500386	24.9893	25.57613	106.0636	0.0030672	-0.04679	58.45372	817.2098	255.608	549.6654	314.0217	1366.836
7	0.499033	24.98788	25.56528	106.0637	0.0030372	-0.04676	58.44967	817.1976	255.6058	549.6622	314.0155	1366.82
7.2	0.497954	24.98722	25.55624	106.0636	0.0030115	-0.04674	58.44908	817.1852	255.6034	549.6548	314.0124	1366.8
7.4	0.497354	24.98831	25.5427	106.0635	0.0029995	-0.04674	58.45187	817.1728	255.6013	549.6475	314.0132	1366.781
7.6	0.497894	24.99503	25.52726	106.0635	0.0029837	-0.04676	58.45211	817.1594	255.6001	549.6442	314.0122	1366.764
7.8	0.499361	25.00448	25.5167	106.0633	0.0029591	-0.04678	58.44923	817.1473	255.5973	549.6424	314.0065	1366.75
8	0.501221	25.00513	25.5125	106.0632	0.002938	-0.04681	58.44876	817.1401	255.5919	549.6396	314.0006	1366.74
8.2	0.502637	24.98991	25.51749	106.063	0.0029278	-0.04684	58.44931	817.1349	255.5833	549.6375	313.9925	1366.733
8.4	0.503498	24.97276	25.53091	106.0629	0.0029262	-0.04688	58.45291	817.1278	255.5735	549.6339	313.9864	1366.722
8.6	0.50349	24.96991	25.54104	106.0627	0.0029134	-0.0469	58.45815	817.1221	255.5706	549.6291	313.9888	1366.712
8.8	0.503262	24.97898	25.54057	106.0626	0.0028842	-0.04688	58.46669	817.1233	255.5764	549.6251	314.003	1366.709
9	0.50305	24.99025	25.54295	106.0626	0.0028552	-0.04683	58.47749	817.1323	255.5848	549.6221	314.0223	1366.715
9.2	0.502795	24.99947	25.55532	106.0628	0.0028354	-0.0468	58.49052	817.1454	255.5932	549.6133	314.0437	1366.719
9.4	0.502405	25.00544	25.56878	106.0629	0.0028147	-0.04682	58.50215	817.1527	255.5964	549.5995	314.0586	1366.713
9.6	0.50234	25.00075	25.56866	106.063	0.0027923	-0.04687	58.51212	817.1523	255.594	549.5875	314.0661	1366.7
9.8	0.502756	24.98866	25.55994	106.0631	0.0027835	-0.04691	58.51987	817.1488	255.5887	549.5805	314.0685	1366.69
10	0.503482	24.97313	25.55404	106.0632	0.002786	-0.04694	58.52066	817.1435	255.5826	549.5776	314.0633	1366.682
10.2	0.503646	24.96003	25.5508	106.0633	0.0027827	-0.04695	58.50949	817.136	255.5762	549.5778	314.0457	1366.674
10.4	0.50309	24.95981	25.54279	106.0633	0.0027688	-0.04694	58.48655	817.1232	255.576	549.5811	314.0226	1366.665
10.6	0.502025	24.96591	25.54016	106.0632	0.0027631	-0.04693	58.45426	817.0969	255.579	549.5815	313.9933	1366.639
10.8	0.501227	24.97539	25.54519	106.0631	0.002762	-0.04693	58.41796	817.0588	255.5841	549.5814	313.962	1366.601
11	0.501692	24.97956	25.55209	106.0631	0.0027513	-0.04692	58.39017	817.023	255.5908	549.5832	313.9409	1366.567
11.2	0.502469	24.97728	25.56151	106.0631	0.0027393	-0.04693	58.3708	816.9979	255.5936	549.5822	313.9244	1366.54
11.4	0.502933	24.97389	25.57403	106.0631	0.0027374	-0.04696	58.36167	816.9915	255.5921	549.5748	313.9137	1366.527
11.6	0.503181	24.9745	25.58131	106.063	0.0027368	-0.04699	58.37088	817.0024	255.5919	549.5604	313.9227	1366.523
11.8	0.503499	24.97386	25.57435	106.063	0.0027195	-0.04698	58.39754	817.0168	255.5935	549.5431	313.951	1366.52

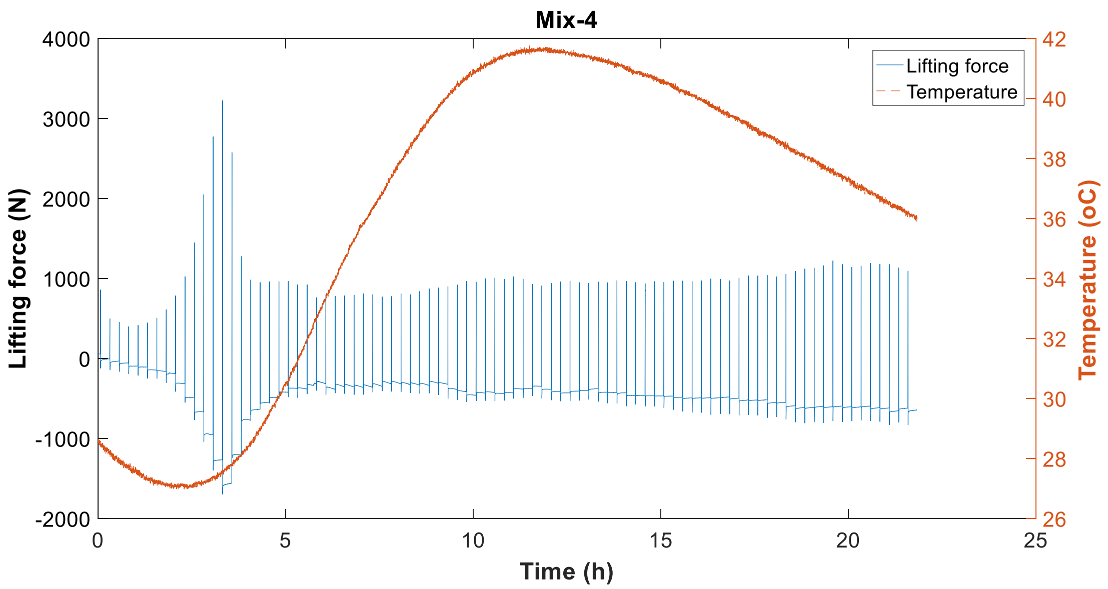
Mix 6

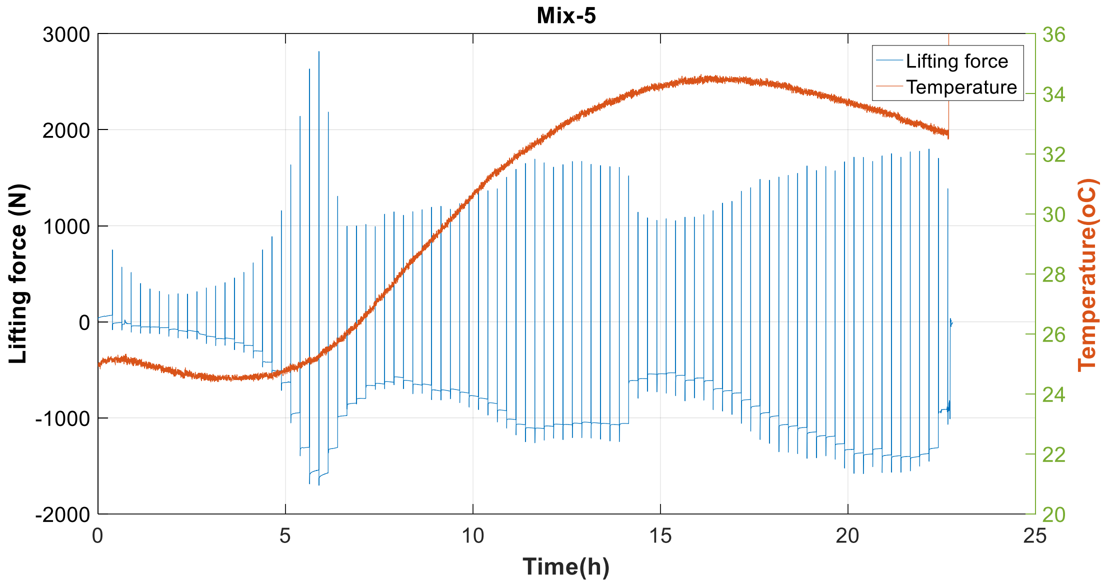
Time(s)	Position (mm)	T1 (ºC)	T2 (ºC)	T3 (ºC)	Pore pressure (bar)	Tension wall (KN)	Right upper (N)	Right lower (N)	Left upper (N)	Left down(N)	Total upper (N)	Total lower (N)
0	0.516696	33.57854	33.71498	106.063	0.0392831	0.0045524	232.5869	799.5645	207.0882	632.0983	439.6351	1431.623
0.2	0.515789	33.57461	33.71537	106.0631	0.0392498	0.0045759	232.5822	799.5524	207.0844	632.0993	439.6266	1431.612
0.4	0.515819	33.56608	33.71428	106.0631	0.0392043	0.0045909	232.576	799.5439	207.0816	632.0913	439.6176	1431.596
0.6	0.516429	33.56266	33.70875	106.0631	0.0391354	0.0045949	232.5717	799.5431	207.0807	632.0814	439.6124	1431.585
0.8	0.516932	33.56552	33.70454	106.0631	0.0390541	0.0045785	232.5708	799.5467	207.0787	632.0746	439.6095	1431.582
1	0.516779	33.56665	33.70611	106.063	0.0389766	0.004567	232.5752	799.5524	207.0745	632.0741	439.6097	1431.587
1.2	0.516184	33.56188	33.70942	106.063	0.0389178	0.0045695	232.5812	799.5639	207.0705	632.0814	439.6116	1431.606
1.4	0.516044	33.55106	33.71379	106.0629	0.0388794	0.0045671	232.5859	799.5785	207.0667	632.0953	439.6125	1431.634
1.6	0.516228	33.53986	33.71779	106.0628	0.0388476	0.0045568	232.5909	799.5884	207.0611	632.1094	439.612	1431.658
1.8	0.516893	33.53196	33.71983	106.0628	0.0388077	0.0045622	232.5945	799.596	207.0563	632.116	439.6107	1431.672
2	0.518479	33.53422	33.71782	106.0628	0.0387571	0.0045739	232.5947	799.6014	207.0547	632.1163	439.6093	1431.678
2.2	0.520595	33.54237	33.71026	106.063	0.0386951	0.0045672	232.5917	799.602	207.0523	632.1127	439.6039	1431.675
2.4	0.522259	33.55326	33.70094	106.0631	0.0386209	0.0045472	232.5891	799.6019	207.0477	632.1123	439.5967	1431.675
2.6	0.522636	33.55861	33.69327	106.0632	0.0385519	0.0045342	232.5836	799.5988	207.0423	632.1145	439.5859	1431.674
2.8	0.521459	33.55246	33.69083	106.0631	0.0385028	0.0045362	232.5767	799.5907	207.036	632.1177	439.5727	1431.669
3	0.519137	33.54489	33.69532	106.063	0.0384734	0.004529	232.5715	799.5823	207.0275	632.1208	439.559	1431.664
3.2	0.516963	33.54466	33.70665	106.0629	0.0384515	0.0045132	232.5723	799.5788	207.0196	632.1254	439.5519	1431.665
3.4	0.515655	33.55131	33.72326	106.063	0.0384277	0.0044936	232.5763	799.5795	207.0148	632.1304	439.5512	1431.67
3.6	0.515489	33.55468	33.73812	106.0631	0.0383987	0.0044727	232.5766	799.5831	207.0116	632.134	439.5481	1431.677
3.8	0.515865	33.54408	33.74882	106.0631	0.0383522	0.0044747	232.5704	799.5862	207.011	632.1346	439.5414	1431.681
4	0.516222	33.52811	33.75378	106.0631	0.0382774	0.0045008	232.5622	799.5897	207.0181	632.1346	439.5403	1431.685
4.2	0.516367	33.52051	33.756	106.063	0.0381944	0.0045199	232.5544	799.5917	207.0273	632.1335	439.5416	1431.686
4.4	0.516233	33.52389	33.75817	106.063	0.0381247	0.0045078	232.5536	799.595	207.0273	632.13	439.5408	1431.685
4.6	0.515936	33.53354	33.76048	106.063	0.0380713	0.0044872	232.5623	799.6041	207.018	632.1287	439.5402	1431.693
4.8	0.516168	33.53791	33.76232	106.0631	0.038031	0.0044744	232.5757	799.6152	207.0079	632.1293	439.5435	1431.705
5	0.516699	33.53777	33.76178	106.0631	0.0380009	0.004454	232.5839	799.6218	206.9991	632.1277	439.543	1431.71
5.2	0.517048	33.5416	33.75776	106.063	0.0379701	0.0044459	232.5868	799.6245	206.993	632.1238	439.5398	1431.709
5.4	0.517154	33.54969	33.75468	106.0629	0.0379256	0.004473	232.5852	799.6195	206.9869	632.1219	439.532	1431.702
5.6	0.517449	33.55348	33.75528	106.0628	0.0378731	0.0044985	232.5837	799.6057	206.9816	632.1254	439.5252	1431.691
5.8	0.518689	33.55061	33.75546	106.0628	0.0378198	0.0045054	232.5835	799.5906	206.9807	632.1329	439.5242	1431.684
6	0.520106	33.54348	33.75291	106.0628	0.0377603	0.0045081	232.5838	799.5807	206.985	632.1402	439.5288	1431.681
6.2	0.520756	33.52693	33.74942	106.0627	0.037699	0.0044993	232.5831	799.579	206.9872	632.1442	439.5303	1431.684
6.4	0.520515	33.5129	33.74702	106.0626	0.0376499	0.0044777	232.5832	799.5854	206.9816	632.1442	439.5247	1431.69
6.6	0.519718	33.51259	33.74688	106.0625	0.0376165	0.0044518	232.5834	799.5956	206.9715	632.1412	439.5149	1431.697
6.8	0.518928	33.52174	33.7499	106.0626	0.03759	0.0044365	232.5833	799.6056	206.9636	632.1373	439.5069	1431.703
7	0.518934	33.53625	33.75283	106.0627	0.0375619	0.0044381	232.5828	799.6122	206.9601	632.1341	439.5028	1431.707
7.2	0.519374	33.55265	33.75507	106.0628	0.0375268	0.0044525	232.5835	799.6184	206.9595	632.1367	439.503	1431.715
7.4	0.519469	33.56498	33.75763	106.0629	0.037487	0.0044626	232.5888	799.622	206.9581	632.1429	439.5069	1431.725
7.6	0.51941	33.57038	33.7596	106.0628	0.0374457	0.0044623	232.599	799.6174	206.9527	632.1474	439.5117	1431.725
7.8	0.519162	33.56579	33.75897	106.0627	0.0374104	0.0044507	232.6105	799.6078	206.9438	632.1498	439.5143	1431.718
8	0.51877	33.55901	33.7604	106.0625	0.0373819	0.0044457	232.6175	799.5997	206.937	632.1517	439.5144	1431.712
8.2	0.518392	33.55091	33.76719	106.0625	0.0373675	0.0044408	232.6196	799.5938	206.9366	632.1554	439.5162	1431.71
8.4	0.517777	33.54314	33.77813	106.0625	0.0373548	0.0044257	232.6195	799.5906	206.9425	632.1555	439.5219	1431.707
8.6	0.51742	33.54266	33.78551	106.0625	0.0373316	0.0044183	232.6171	799.5906	206.946	632.1502	439.5231	1431.701
8.8	0.519139	33.55045	33.78604	106.0627	0.0373012	0.0044162	232.6125	799.5896	206.9404	632.1462	439.5129	1431.696
9	0.52183	33.5629	33.78184	106.0628	0.0372716	0.0043998	232.6063	799.5934	206.9281	632.1472	439.4944	1431.701
9.2	0.522504	33.5752	33.776	106.063	0.0372439	0.0043897	232.6038	799.608	206.9199	632.1497	439.4837	1431.718
9.4	0.521235	33.58473	33.77427	106.0631	0.0372189	0.0044104	232.608	799.6284	206.919	632.1517	439.4869	1431.741
9.6	0.519667	33.58861	33.77451	106.0632	0.0371973	0.0044535	232.6146	799.6485	206.9214	632.156	439.496	1431.765
9.8	0.518479	33.58502	33.77341	106.0632	0.0371768	0.0044796	232.6213	799.6596	206.922	632.1602	439.5033	1431.78
10	0.517767	33.57776	33.77673	106.0633	0.0371607	0.0044614	232.6256	799.6592	206.919	632.1639	439.5046	1431.783
10.2	0.517506	33.56599	33.78469	106.0634	0.0371468	0.0044244	232.6274	799.653	206.916	632.1655	439.5033	1431.779
10.4	0.517239	33.5637	33.79119	106.0635	0.0371363	0.0043959	232.6266	799.6449	206.9138	632.1644	439.5003	1431.77
10.6	0.517061	33.56797	33.79287	106.0636	0.0371235	0.0043814	232.6206	799.6376	206.9143	632.1615	439.4948	1431.759
10.8	0.517041	33.5735	33.79185	106.0634	0.0370949	0.0043859	232.614	799.6352	206.9166	632.1631	439.4906	1431.759
11	0.517353	33.57874	33.78988	106.0632	0.0370464	0.0044037	232.6135	799.6362	206.9171	632.1707	439.4906	1431.767
11.2	0.517683	33.58686	33.78815	106.0631	0.0369923	0.0044115	232.6183	799.6429	206.9131	632.1796	439.4914	1431.783
11.4	0.517994	33.5999	33.78831	106.063	0.0369458	0.0044213	232.6245	799.6548	206.9101	632.1854	439.4945	1431.801
11.6	0.517898	33.61218	33.7915	106.0629	0.0369095	0.0044398	232.6311	799.668	206.9119	632.1895	439.503	1431.818
11.8	0.517288	33.61204	33.79638	106.0627	0.0368934	0.0044664	232.6371	799.6778	206.9112	632.1935	439.5083	1431.832

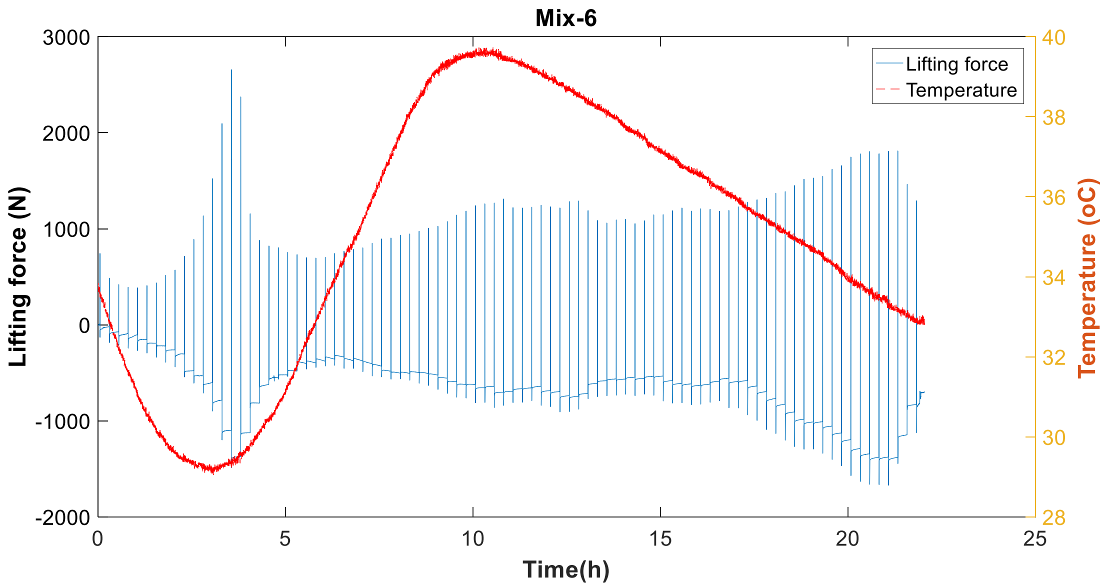
Appendix 2 – Figures from the raw data

Temperature and Lifting force

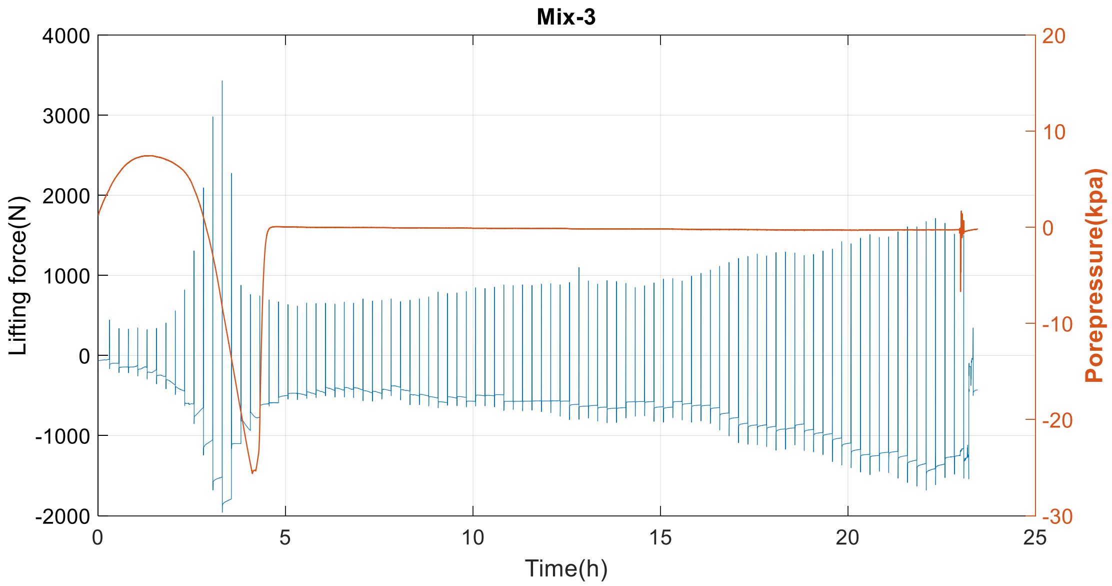


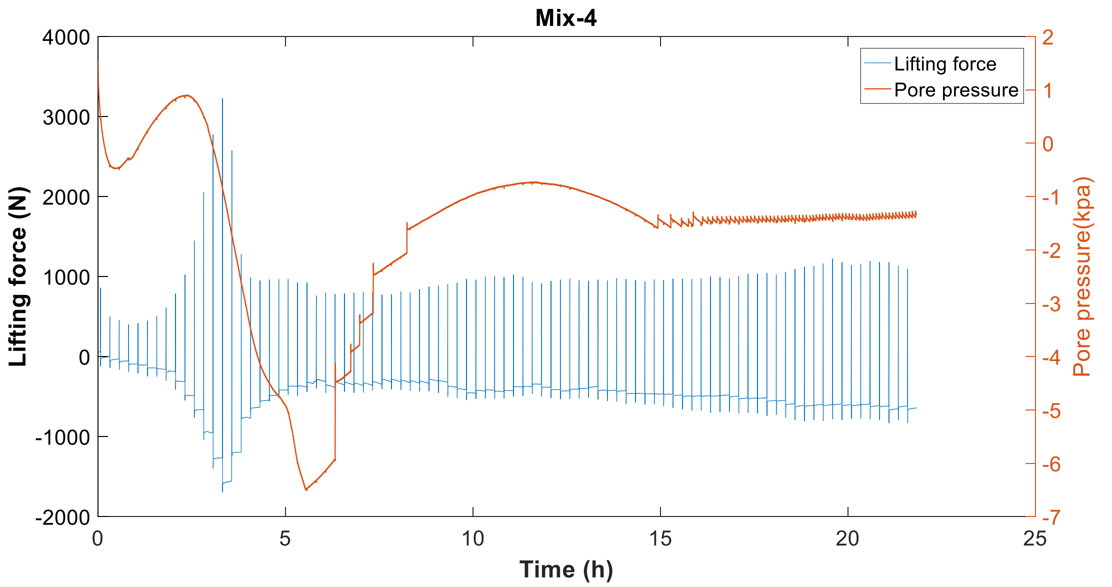


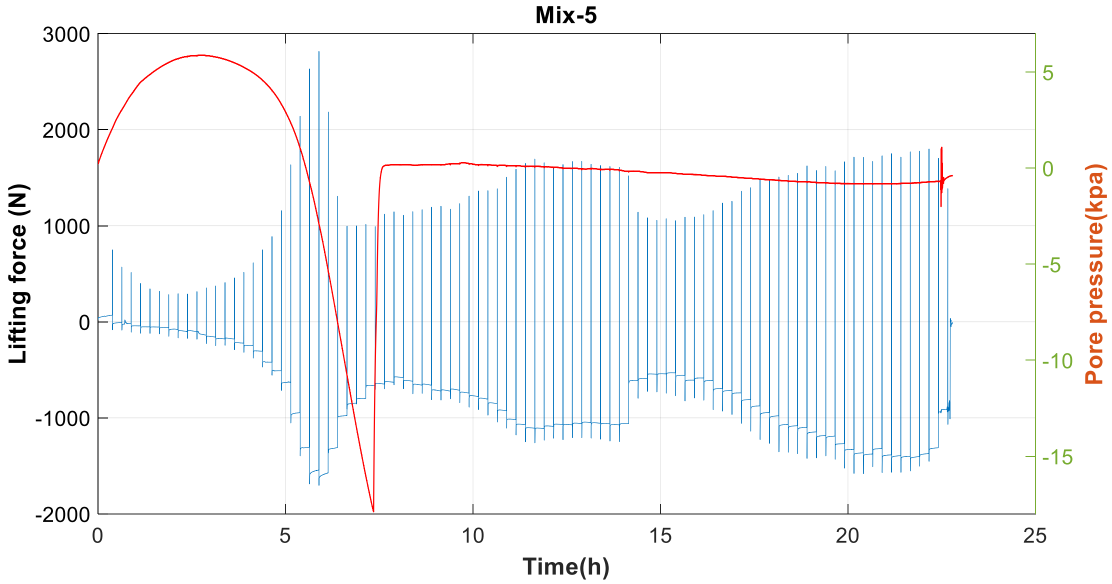

Mix-5
3000
2000
1000
0
-1000
-2000
Lifting force (N)
0
5
10
15
20
25
Time(h)
36
34
32
30
28
26
24
22
20
Temperature(oC)
Lifting force
Temperature


Mix-6
3000
2000
1000
0
-1000
-2000
Lifting force (N)
0
5
10
15
20
25
Time(h)
40
38
36
34
32
30
28
Temperature (oC)
Lifting force
Temperature

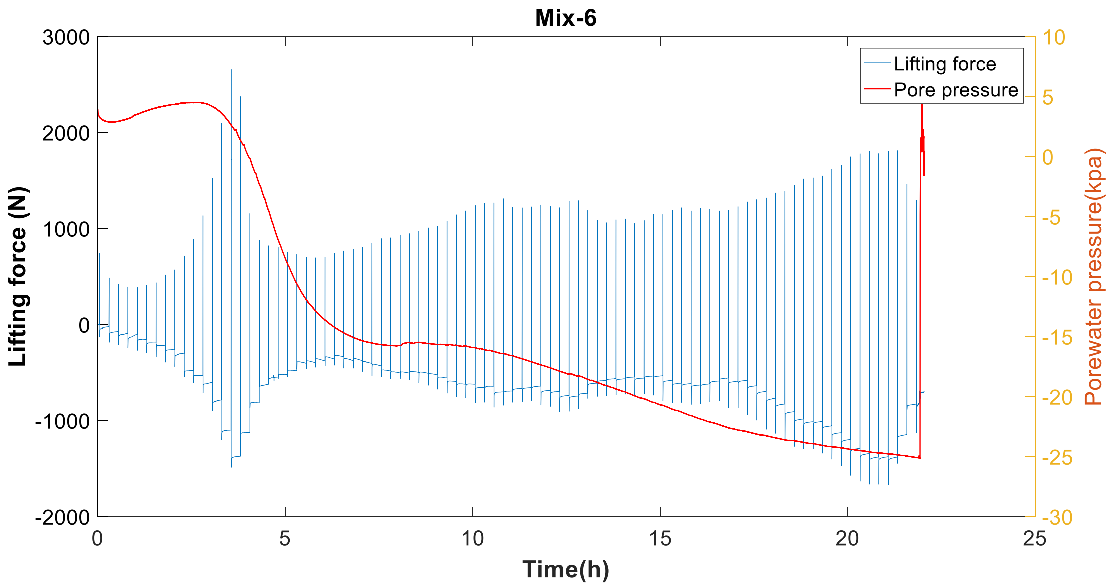
Pore pressure and Lifting force





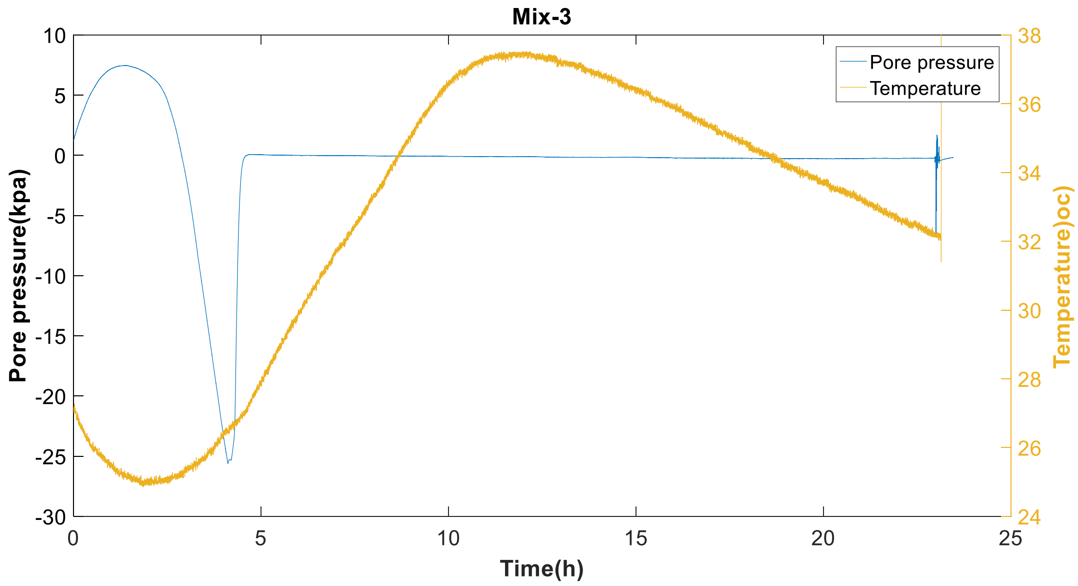


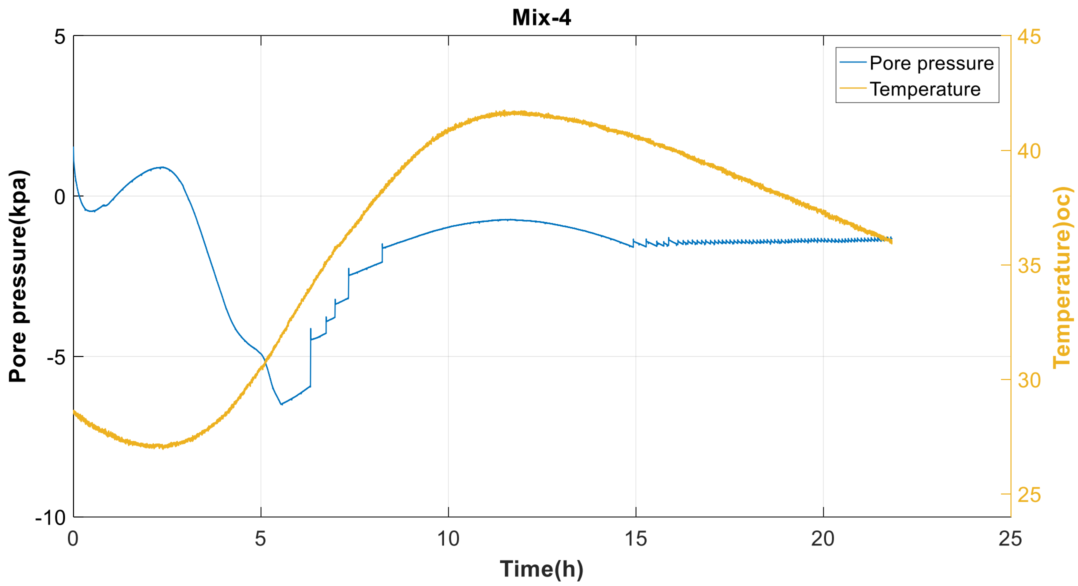
Mix-5
Lifting force (N)
Pore pressure(kpa)
Time(h)

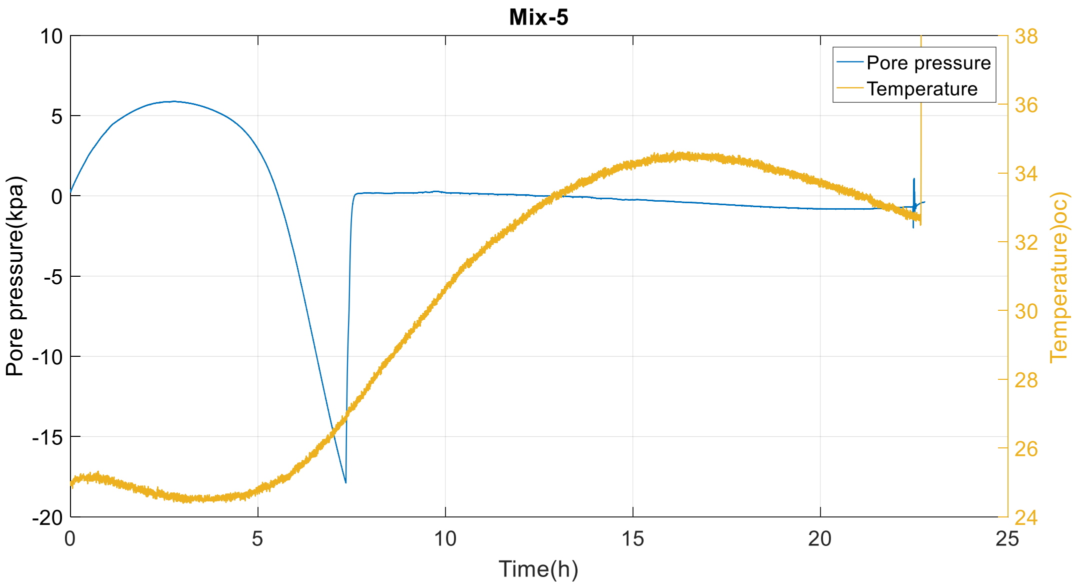


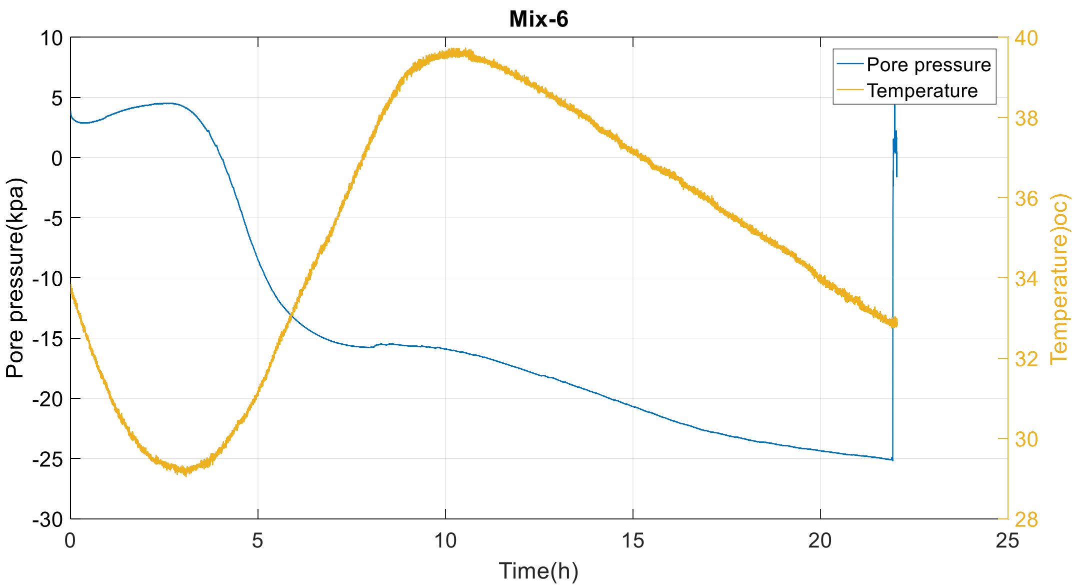
Mix-6
Lifting force
Pore pressure
Lifting force (N)
Porewater pressure(kpa)
Time(h)

Temperature development and pore pressure

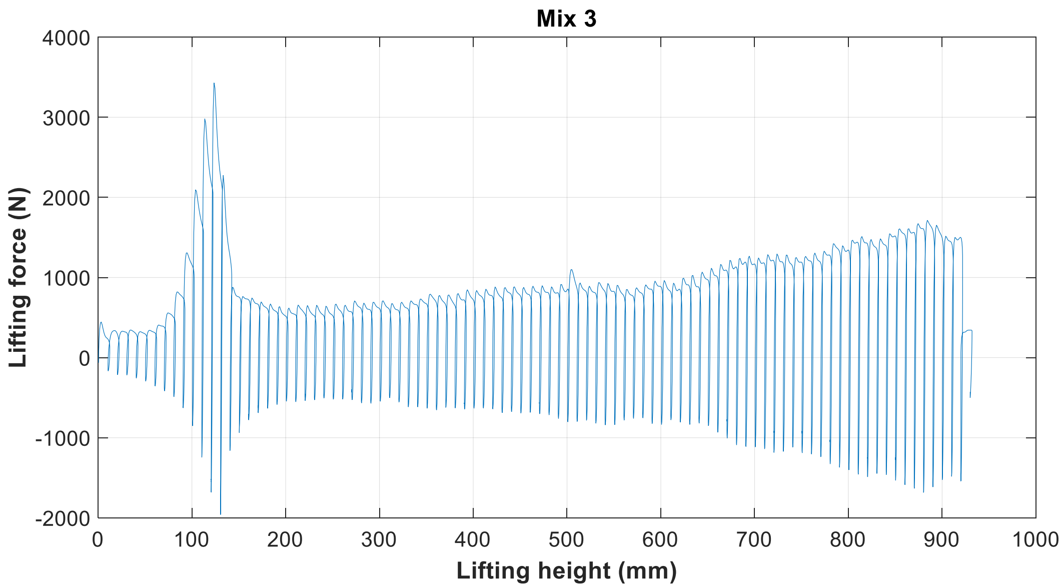


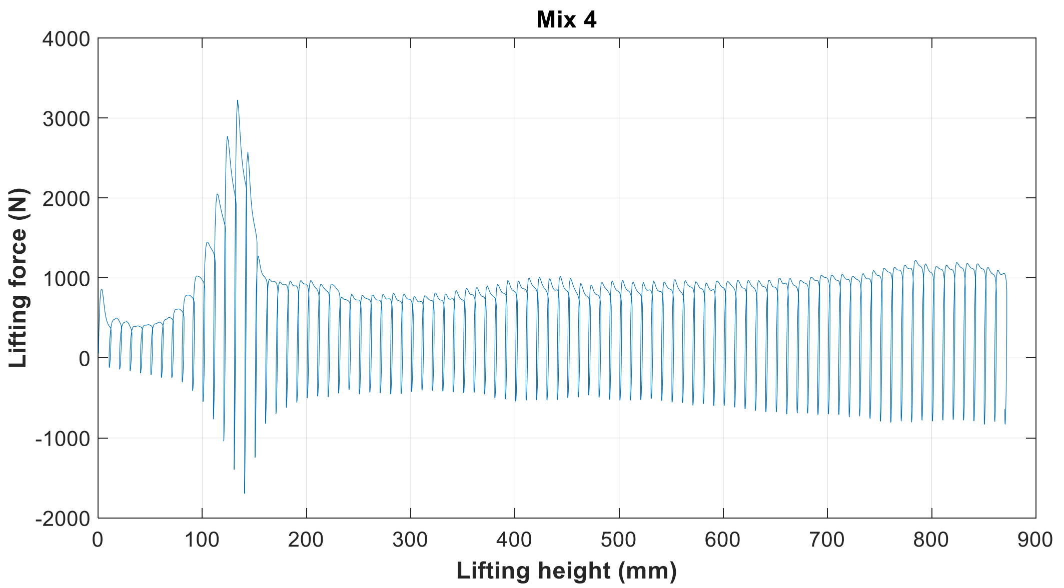


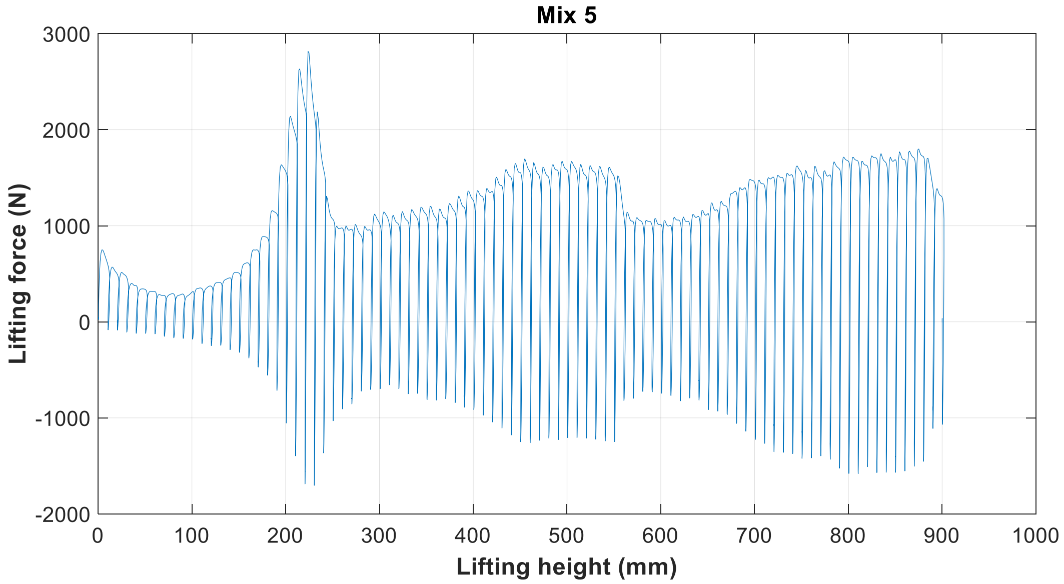

Mix-5
Pore pressure
Temperature
Pore pressure(kpa)
Temperature)oc)
Time(h)
10
5
0
-5
-10
-15
-20
38
36
34
32
30
28
26
24
0
5
10
15
20
25

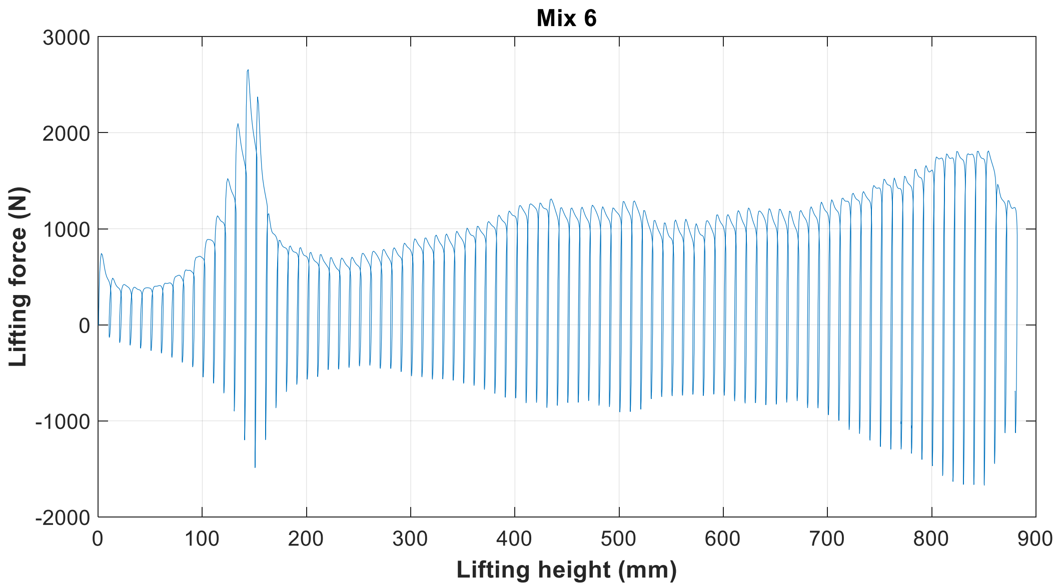

Mix-6
Pore pressure
Temperature
Pore pressure(kpa)
Temperature)oc)
Time(h)
10
5
0
-5
-10
-15
-20
-25
-30
40
38
36
34
32
30
28
0
5
10
15
20
25

Lifting height and Lifting force






Mix 5
3000
2000
1000
0
-1000
-2000
Lifting force (N)
0
100
200
300
400
500
600
700
800
900
1000
Lifting height (mm)


Mix 6
3000
2000
1000
0
-1000
-2000
Lifting force (N)
0
100
200
300
400
500
600
700
800
900
Lifting height (mm)

Appendix 3 – Anleggsement FA

PRODUCT DATA SHEET

ANLEGGSEMENT FA

CEM II/A-V

LAST REVISION MARCH 2019

The cement satisfies the requirements according to NS-EN 197-1:2011 to Portland-fly ash cement CEM II/A-V 42.5 N.

Properties		Declared values	Requirements according to NS-EN 197-1:2011
Fineness (Blaine m^2/kg)		390	
Specific weight (kg/dm^3)		3.02	
Soundness (mm)		1	≤ 10
Initial setting time (min)		165	≥ 60
Compressive strength (MPa)	1 day	12	
	2 days	21	≥ 10
	7 days	37	
	28 days	53	≥ 42.5 ≤ 62.5
Sulfate (% SO_3)		≤ 3.5	≤ 3.5
Chloride (% Cl^-)		≤ 0.085	≤ 0.10
Water soluble chromium (ppm Cr^{6+})		≤ 2	≤ 2[1]
Alkalies (% Na_2O_{eq})[2]		0.9	
Clinker (%)		81	80-94
Fly ash (%)		15	6 - 20
Limestone (minor additional constituents %)		4	< 5

1. According to EU regulation REACH Annex XVII point 47 Chromium VI compounds.
2. Total alkali content of the cement.

NORCEM
HEIDELBERGCEMENT Group

Norcem AS, P.O Box 142, Lilleaker, N-0216 Oslo
Tlf. 22 87 84 00 firmapost@norcem.no www.norcem.no

Appendix 4 – Dynamon SX-N

12.11

Dynamon SX-N

Superplastiserende tilsetningsstoff

PRODUKTBESKRIVELSE

Dynamon SX-N er et svært effektivt superplastiserende tilsetningsstoff basert på modifiserte akrylpolymerer.

Produktet tilhører Dynamonsystemet basert på den Mapeiutviklede DPP-teknologien (DPP = Designed Performance Polymers) der tilsetningsstoffenes egenskaper skreddersys til ulike betongformål.

Dynamonsystemet er utviklet på basis av Mapeis egen sammenstilling og produksjon av monomerer.

BRUKSOMRÅDE

Dynamon SX-N er et tilnærmet allround-produkt som er anvendelig i all betong for å øke støpeligheten og/eller redusere tilsatt vannmengde.

Noen spesielle bruksområder er:

- Vanntett betong med krav til høy eller svært høy fasthet og med strenge krav til bestandighet i aggressive miljøer.
- Betong med særlige krav til høy støpelighet, i konsistensklasser S4 og S5 etter NS-EN 206-1.
- Selvkomprimerende betong med ønske om lengre åpentid. Om nødvendig kan SKB stabiliseres med en viskositetsøker - **Viscofluid** eller **Viscostar**.
- Til produksjon av frostbestandig betong – da i kombinasjon med luftinnførende tilsetningsstoffer – **Mapeair**. Valg av type luftinnførende stoff gjøres ut fra egenskapene til de andre delmaterialer som er tilgjengelige.
- Til gulvstøp for å oppnå en smidig betong med bedret støpelighet. Store doseringer og lave temperaturer kan retardere betongen noe.

EGENSKAPER

Dynamon SX-N er en vannløsning av aktive akrylpolymerer som effektivt dispergerer (løser opp) sementklaser.

Denne effekten kan prinsipielt utnyttes på tre måter:

1. For å redusere mengden tilsatt vann, men samtidig beholde betongens støpelighet. Lavere v/c-forhold gir høyere fasthet, tetthet og bestandighet i betongen.
2. For å forbedre støpeligheten sammenlignet med betonger med samme v/c-forhold. Fastheten forblir dermed den samme, men muliggjør forenklet utstøping.
3. For å redusere både vann og sementmengde uten å forandre betongens mekaniske styrke. Gjennom denne metoden kan en blant annet redusere kostnadene (mindre sement), redusere betongens svinnpotensial (mindre vann) og redusere faren for temperaturgradienter på grunn av lavere hydratasjonsvarme. Spesielt er denne siste effekten viktig ved betonger med større sementmengder.

VÆR OPPMERKSOM PÅ

Dynamon SX-N lar seg kombinere med andre Mapei tilsetningsstoffer, som f.eks størkningsakselererende stoffer som **Mapequick** og størkningsretard-erende stoffer som **Mapetard**. Produktet lar seg også kombinere med luftinnførende tilsetningsstoffer, **Mapeair**, for produksjon av frostbestandig betong.

Produsent:
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post@mapei.no
www.mapei.com