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Comparative Study of Self-Sealing and Self-Healing in Clay and Concrete

ADDITIONAL GRADUATION WORK

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ABSTRACT

Study of self-sealing and self-healing in clay is a fascinating topic which can be applied in many fields namely in construction sector or as the underground nuclear waste repository. However, lack of references still hinders the advancement of such field. Meanwhile, more advance researches are available for self-sealing and self-healing in concrete. Therefore, this project is held to find whether any valuable lessons from extensive researches of self-sealing and self-healing in concrete which can be applied to the development of the study in clay. This research is a comparative literature study of self-sealing and self-healing mechanism between clay and concrete based on four aspects i.e. hydraulic, thermal, chemical and mechanical which based on the published papers from scientific journals and books. In terms of hydraulic aspect, hydraulic gradient plays an important role for sealing and healing mechanism in both clay and concrete. For thermal aspect, hydraulic conductivity is not affected by the temperature increased in clay while sealing and healing rate are improved for the similar condition in concrete. In chemical aspect, high pH environment increases sealing rate of concrete while high salinity decreases the capacity of sealing and healing of clay. For mechanical aspect, both concrete and clay experience a decreasing hydraulic conductivity under increasing confining stress. All of the results showed that both clay and concrete experience self-sealing and self-healing mechanism with different influences by each aforementioned aspect.

1. Introduction

1.1. General

Self-healing and self-sealing material are the topics which attract mankind since long time ago. It is started with the human observation to nature which involve the ability of tree to regrow its branch after being pruned, recovery of skin to stop the wound or bone improvement after injury. These capabilities are the subjects which have been recreated by human and to be applied in their daily life. Such knowledge can be applied in various field ranging from infrastructure sector to medical application. The purpose for studying such phenomena is to lengthen the lifetime of product so that it increases economical value and human safety.

1.2. Background

It is believed the modern application of self-healing and self-sealing material was started in Roman empire. They mix volcanic ash-lime mortar as the binder element in concrete which also has a distinct characteristic of self-healing. The mechanism is induced by the reaction between mortar and air moisture which leads to the dissolution and reprecipitation (Sánchez-Moral et al., 2004). Such innovation was the consideration for categorizing the Roman concrete as the blueprint of modern concrete to this day. Even though it is not completely clear whether people at that time was aware that this compound has a sealing and healing capability and deliberately added it to their concrete mix, the fact that Roman infrastructure still standing for centuries amazes people nowadays. Such condition then drove scientists and engineers to do plenty of research to have a deeper understanding of the characteristic of Roman concrete. Since concrete is a man-made structure, it has more flexibility to determine the final characteristic. The implication of such condition is there are so many advancements in concrete technology, including in self-sealing and self-healing aspect.

As time goes by, the research has developed into more advance state. Increasing rate for space exploration in 1970's leaded to the extensive research in self-sealing and self-healing in polymer and composites (Wool, 2008). Then in the late 1980's, the research was started to investigate such mechanism in geological formation such as basalt, granite or salt dome as the alternatives for nuclear waste storage (Briggs et al., 1990). This is continued to the vast studies in clay which has low hydraulic conductivity with self-sealing and self-healing capability, in which as one of the components to ensure the safety factor in the underground nuclear waste. Such capability came from the reaction between water and groups of clay minerals which has the capacity of swelling and shrinking. This capability then transforms to the opening and closing of discontinuity which later affects to the magnitude of hydraulic conductivity. When the particle swells, discontinuities in clay gets closer, thus hydraulic conductivity decreases. However, even though the detail understanding of self-sealing and self-healing is not the main interest for performance assessment of nuclear waste repository, a well-established knowledge of such mechanism is still needed to explain other possible application of self-sealing and self-healing aside of nuclear waste repository.

1.3. Research Phases

This research is a comparative study between clay and concrete which based on the perspectives of several aspects i.e. hydraulic, thermal, chemical and mechanical. Such aspects are used in order to have a better understanding of self-sealing and self-healing mechanism. Concrete is chosen as the comparator to clay because of its abundance references which cover aspects mentioned. Resources of the research are based on the existing studies which comprises of both in-situ experimental and laboratory tests. The aim of the study is to find the valuable lessons after many years of research in concrete which can be applied in the study of self-sealing and self-healing in clay.

The step of the study is started with initiating the problem analysis which includes determining the scope of research and defining the aspects which affect the sealing and healing mechanism. Next step is the literature study to collect all the data needed until it is considered sufficient. After all relevant sources are collected, next process is analyzing the data and generate a comparison between sealing and healing mechanism in clay and concrete. The last step is to derive a conclusion with some remarks. The flow chart of the research is depicted under the figure below:

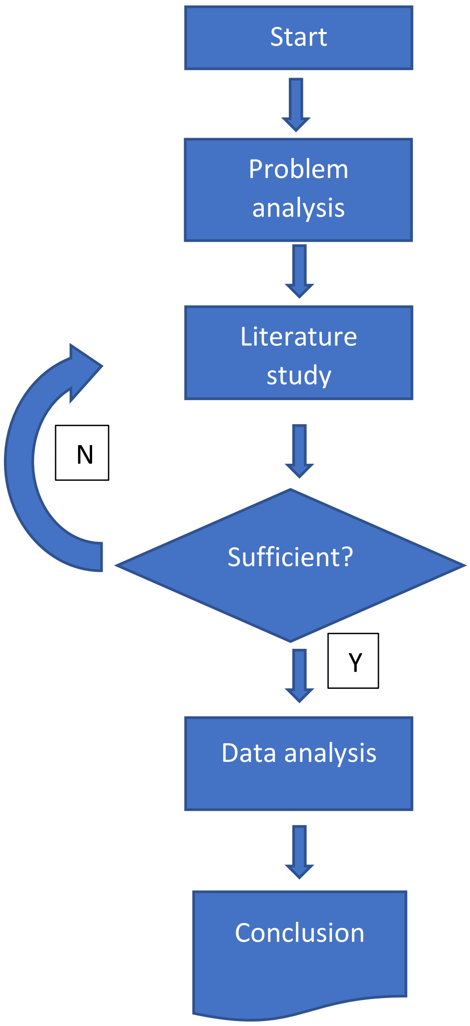

Fig 1. Research flow chart

1.4. Definitions

There are several point-of-views when it comes to the definition of the mechanism. One from material science field defines self-healing as the materials that possess the ability to fully or partially recover a functionality that is mediated by operational use (Bekas et al., 2016). Other define it as the ability of a material to heal (recover/repair) damages automatically and autonomously, that is, without any external intervention (Ghosh, 2009). The highlighted idea of both definitions concerns to the recovery level and self-governing mechanism while they do not elaborate more to the self-sealing capacity.

Other perspective comes from Bernier et al. (2007) which define "sealing" as the reduction of fracture permeability by any hydromechanical, hydrochemical, or hydro-biochemical process while "healing" is a sealing with loss of memory of the pre healing state. They also defined the term "self" as a healing or sealing process which happens spontaneously without any intervention from human actions.

Another definition comes from Hearn (1998) whose addressing the mechanism under the term "autogenous healing" which defined as the ability of cement to heal cracks in fractured concrete. Such mechanism can be observed through decreasing permeability in time. Based on two definitions above, it can be concluded that the mechanism may occur under water-dependent condition.

In this research, a slightly modified definition is proposed based on the scope of work. It is suggested for *self-healing* term is defined as the recovery of specimens under certain thermo-hydro-chemo-mechanical condition while *self-sealing* is defined as the reducing flow through specimens as the result of self-healing mechanism. The term *specimens* in both definitions above refers to either clay or concrete.

2. Material Description: Clay

This chapter discusses the mechanism of self-sealing and self-healing in clay. The first subchapter, Structure and Description, will explain the definition and mineralogy of clay, while the second subchapter will describe general processes of sealing and healing in clay. The last subchapter deals with the findings from previous studies: the sealing and healing process in clay on the basis of four aspects, namely hydraulic, thermal, chemical and mechanical aspects.

2.1. Structure and Description

Definitions

Various definitions have been suggested to describe the term “clay”. The earliest and most common definition of clay originates from Wentworth (1922), stating that clay is the particle of clastic sediment which has diameter size of approximately 1/256 mm. This is the finest particle among other clastic sediment based on Wentworth’s grade term. The term also differentiates between loose particle (The aggregate) and compacted particle (The Indurated Rock). Instead, this research discusses clay in general form and do not restrict the definition based on the looseness or compactness of the particle.

Table 1. The Wentworth’s grade terms with modification. Area inside red border is the description of clay. (from Wentworth (1922))

Size (mm)	The pieces	The aggregate	The indurated rock
>256	Bowlder	Bowlder gravel	Bowlder conglomerate
64-256	Cobble	Cobble gravel	Cobble conglomerate
4-64	Pebble	Pebble gravel	Pebble conglomerate
2-4	Granule	Granule gravel	Granule conglomerate
1-2	Very coarse sand grain	Very coarse sand	Very coarse sandstone
0.5-1	Coarse sand grain	Coarse sand	Coarse sandstone
0.25-0.5	Medium sand grain	Medium sand	Medium sandstone
0.125-0.25	Fine sand grain	Fine sand	Fine sandstone
0.0625-0.125	Very fine sand grain	Very fine sand	Very fine sandstone
0.0039-0.0625	Silt particle	Silt	Siltstone
<0.0039	Clay particle	Clay	Claystone

Clay has distinctive characteristics compare to other material because of its low hydraulic conductivity due to the very-fine grainsize. It also has wide span behavior when it comes in contact with water, as represented in liquid limit, plastic limit, and plasticity index. One type of clay type is able to absorb water easily and can be easily swelled, while others are prone to disintegrate and turn into liquid-like structure (quick clay). For the purpose of this research, we intend to apply one definition of clay based on its ability of sealing and healing.

Clay Minerals

Similar to other materials such as rocks or loose sediments, clay consists of minerals as its main constituent. The general structures of clay minerals comprise of silicate minerals sheet, defined as phyllosilicates, which forms tetrahedral (T) and octahedral (O) geometry (Fig 2). The element of tetrahedral consists of four oxygen atoms with one cation in the center, generally Si^{4+}, Al^{3+}, or Fe^{3+}. Three oxygen atoms on the base of geometry are called basal oxygen (Ob) and one oxygen atoms on the top of geometry is called apical oxygen (Oa). Octahedral element is composed of oxygen-hydrogen bond with one cation of Al^{3+}, Fe^{3+}, Mg^{2+}, or Fe^{2+}.

Group of tetrahedral or octahedral linked together to form a *sheet* and group of sheets linked together to form *layer*. In general, such layer contain tetrahedral and octahedral sheets of 1:1 or 2:1 structure. The earlier term comprises of one layer for each tetrahedral and octahedral sheet while the later term refers to one layer of octahedral sheet sandwiched between two tetrahedral sheets (Fig 3).

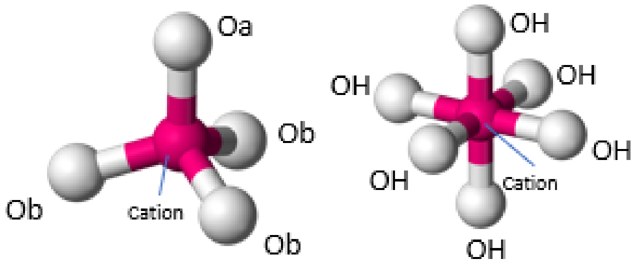

Fig 2. Tetrahedral (left) and octahedral (right) geometry (from https://courses.lumenlearning.com/boundless-chemistry/chapter/molecular-geometry/ with modification)

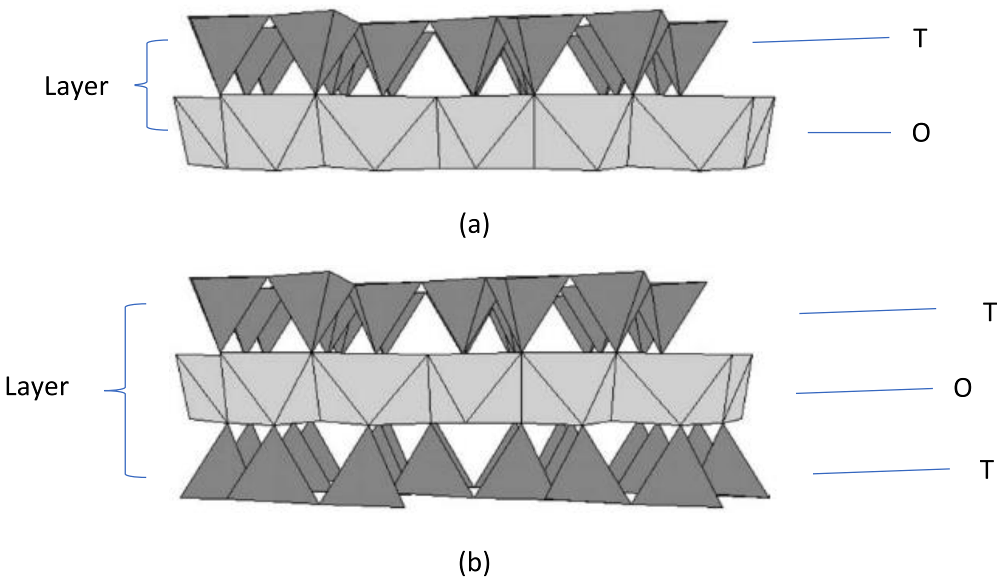

Fig 3. General assembly of clay mineral layer (a) 1:1 structure and (b) 2:1 structure. T: Tetrahedral sheet, O: Octahedral sheet. (from Brigatti et al. (2006))

Layers of octahedral and tetrahedral sheets are linked together to form particle. In between these stacked layers, there is a gap which defined as “interlayer space”. This space might be empty or occupied with cations, water molecule, or with another octahedral sheet (Brigatti et al., 2006). Illustration of interlayer space is depicted under Fig 4. One of the characteristics of interlayer cation, specifically one from 2:1 structure, is they are hydrated and exchangeable. This interchangeable ability is generated from negative layer charge of ions which located at basal oxygen atoms of tetrahedral sheet.

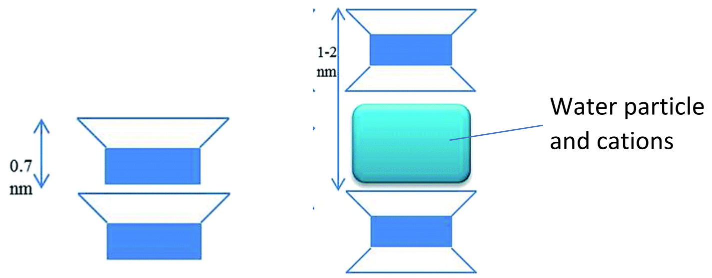

Fig 4. Illustration of 1:1 clay mineral structure with unoccupied interlayer space (left) and 2:1 clay mineral structure with occupied interlayer space (right). In this case the space is occupied with water and other cations (from Ghadiri et al. (2015))

The examples for hydrated 2:1 structure are smectite and vermiculite. Compared to the other groups, smectite and vermiculite groups are the two sets of clay mineral which have shrink-swell capabilities. This capability is an important mechanism of self-sealing and self-healing in clay. Such condition occurs due to the absent of charge variability in other clay mineral groups. A layer which consists of tetrahedral and octahedral sheets would create structure with either neutral or negatively charged. While for most of 2:1 structure has negative charge as discussed in the previous paragraph, for 1:1 structure has close to zero layer charge (Brigatti et al., 2006).

Several attempts have been made in order to observe the mineralogy composition of clay. One experiment from Zeelmaekers et al. (2015) inspected the mineral composition of Boom clay. They found that clay consists of maximum 39% of smectite mineral, 25% of illite, and 42% of illite-smectite. Gaucher et al. (2003) held experiment for Opalinus clay and stated it consists of maximum 76% of combination from illite, illite-smectite, and chlorite while the other 24% is for other non-clay mineral. Other experiments from Zhang (2013) inspected Callovo-Oxfordian argillite (COX) and Opalinus clay (OPA) and found that maximum composition of clay mineral in OPA is 21% higher than COX. Based on these studies, it can be said that clay tend to have capability to shrink swell.

2.2. Self-sealing and self-healing mechanisms

It is mentioned earlier in clay mineral subchapter that smectite group has the interchangeable cations. Such condition allows clay to have a capability to attract or release water particle, leading to the characteristic of swelling and shrinking. This mechanism is caused by the cation substitution located in the interlayer space to one with the lower valency. Thus, additional cation is needed to balance the charge. When water is added, the cations are hydrated then attracted and fill the interlayer space. Eventually, the interlayer space is occupied with cations and water thus increases the distance between the clay particle. This condition is defined as the *expansion*. On the other hand, clay also has a capability to release the water particle which then collapse the interlayer space and decreases its bulk volume. Such condition is called *shrinkage* which considered as a reversible feature to balance the excess of negative charge in clay layer (Brigatti et al., 2006).

The further impact of swelling clay can be observed from decreasing value of hydraulic conductivity. The reduction is caused by decreasing distance of crack in the sample initiated by the swelling capabilities of clay. When in contact with water, the stiffness of specimen is reduced along with its strength, making the specimen weaker than the initial one. Clay particle absorbs water particle and weakens the bonds between the clay particle which is defined as *slaking*. These loose particles then fill the voids and reduce the discontinuity spacing and furthermore reduce the permeability. The statement is supported by Zhang (2013) which stated the mechanism also includes weakening and slaking of particle as additional factor for sealing mechanism.

Another factor which controls swelling and sealing is mineral percentage. One experiment from Pusch (2006) found that higher percentage of smectite could increases swelling pressure and decreases hydraulic conductivity, as depicted under Fig 5. Swelling pressure significantly increases when percentage of smectite is higher than 30%. However, hydraulic conductivity falls drastically when smectite percentage is lower than 30% and furthermore the graph shows less steep progression. This might occur because slaking of clay particle clogs and narrows the discontinuity so that higher smectite percentage is no longer as a primary cause for decreasing hydraulic conductivity.

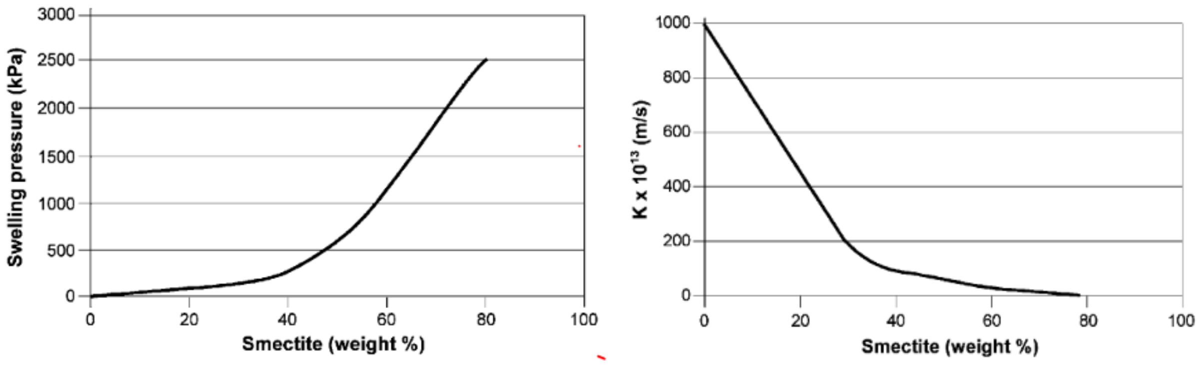

Fig 5. Plot of smectite weight vs swelling pressure (left) and hydraulic conductivity (right) from Pusch (2006)

While most of clays experience self-sealing, the evidence describing the detail of self-healing process has been absent. The term “heal” can be associated to the recovery of specimen to the initial condition after being tested. For example, if the crack in specimen is undiscernible after the test, one can categorize it as “fully-healed”, or if the discontinuity is still visible then it can be categorized as “partially-healed”. However, visual assessment should not be the only parameter to classify the healing mechanism. One should consider mechanical properties as parameter which need to be assessed and make comparison with initial condition.

2.3. Experimental observations

This subchapter explains various experimental result of self-sealing and self-healing in clays. In discussing both mechanisms, we refer to the previous experiments on the hydraulic, thermal, chemical and mechanical aspects of clay. The objective of this subchapter is to give a perception of how different aspects might affect to the sealing and healing mechanism.

Hydraulic Aspect

This section discusses the self-sealing and self-healing mechanism under influence of hydraulic loads. The assessment of self-sealing consists of monitoring of hydraulic conductivity evolution of cracked clay under flowing H_2O (either in the form of liquid or wetted gas). Another assessed mechanism is the swelling process which can be considered as the source of sealing mechanism. For self-healing the assessment was determined by visual condition of cracks after being tested.

Zhang (2013) conducted an experiment to inspect the swelling and sealing mechanism of Callovo-Oxfordian (COX) argillite. In his research, samples were artificially cracked by triaxial apparatus, then injected with dry gas for 24 hours then with wetted gas by increasing relative humidity up to 100% while applying constant confining pressure of 1 MPa for a certain amount of time. The test set up is depicted in Fig 6.

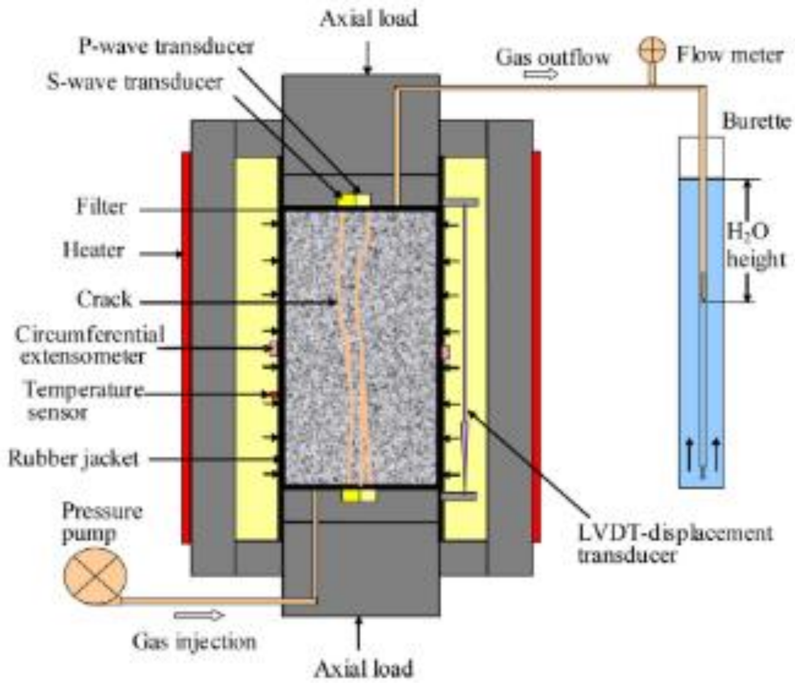

Fig 6. Sealing test of cracked sample in triaxial cell (Zhang, 2013)

Result indicated that a swelling mechanism and decreasing permeability through time. It can be seen from the graph that expansion was higher with increasing relative humidity. Higher relative humidity means higher water content in the air, thus higher possibility for clay to absorb more water particle which can induce swelling. Such condition then induce an aperture closing which made the permeability decreased approximately 1.5 order of magnitude within 40 days. The result is depicted in Fig 7 below. It can be concluded that the expansion and sealing mechanism of clay are not only occur in a saturated or submerged condition but also can be induced under a high humidity environment.

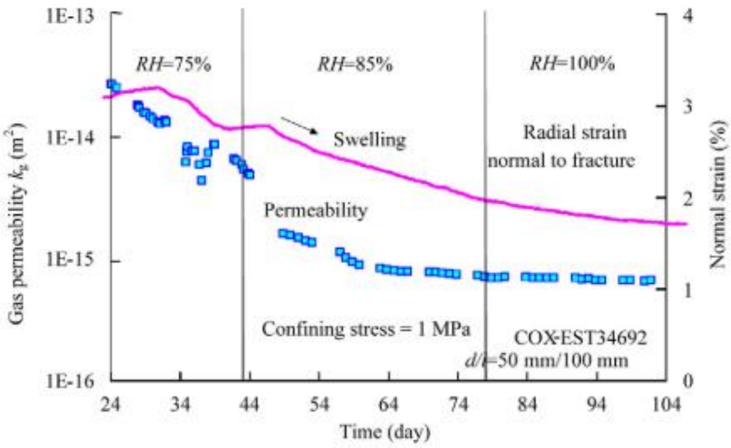

Fig 7. Effects on wetted gas flow on fracture sealing (Zhang, 2013)

Another experiment was conducted by Bernier et al. (2007). They investigated sealing mechanism of Opalinus clay with a modified triaxial test device (Fig 8). The sequence of investigation was started with inserting the specimen into the testing device then permeability of virgin sample was measured. For the next step, the specimen was fractured without removing it from the cell. Then, permeability was monitored through time under flowing water and constant confining stress of 4.5 MPa.

The result showed a sealing mechanism for both specimens. The sample experienced a sudden increase of hydraulic conductivity from range of 10^{-12} m/s to 10^{-8} m/s after being cracked, then it started to decrease up to 1 order of magnitude in approximately 200 days (Fig 9). The result is based on sample D (yellow line) as it gives the most stable result compare to the other experiment. For healing mechanism, discontinuities in Boom clay was undiscernible and visually similar to uncracked specimen while for Opalinus clay the discontinuity was still visible. However, such result was not quantifiable.

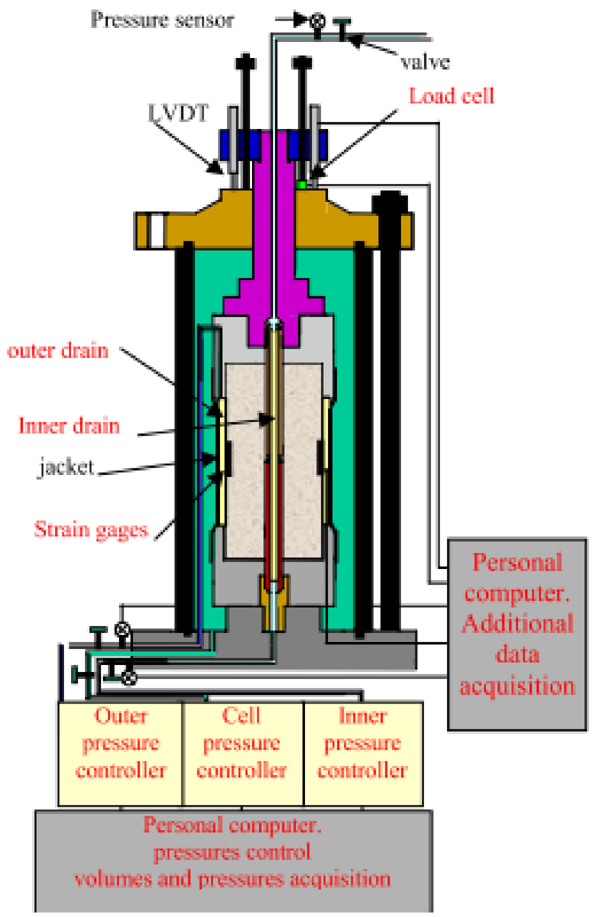

Fig 8. Modified Laboratoire de Geotechnique (LEGEP) testing device (Bernier et al., 2007)

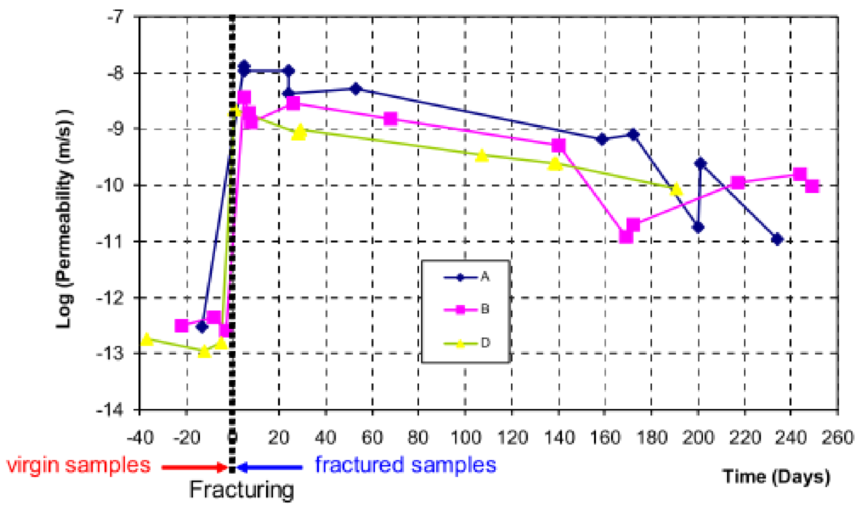

Fig 9. Evolution of the hydraulic conductivity with time in fractured Opalinus Clay samples (Bernier et al., 2007)

Another similar result is obtained from the experiment by Zhang (2018). He examined sealing mechanism of Callovo-Oxfordian (COX) clay under impact of water flow and low confining stress. The confining stress was slowly increased from 2 MPa to 3.5 MPa for over more than 3 years. However, the confining stress for the first 270 days was kept constant at 2 MPa, thus the stress condition is comparable to one from Bernier et al. (2007)'s experiment. Result is shown under Fig 10.

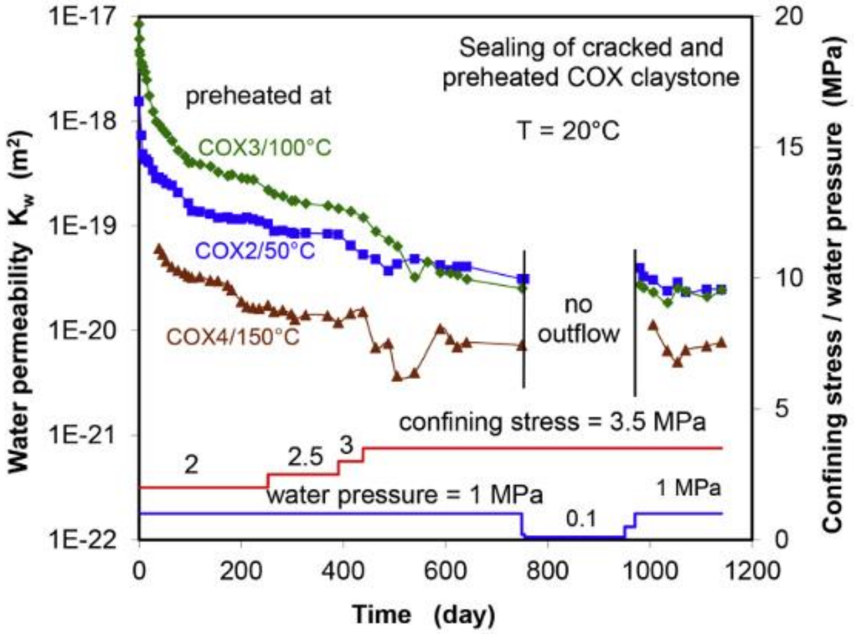

Fig 10. Long term evolution of permeability of COX clay (Zhang, 2018)

In order to make the experimental result from Zhang (2018) become comparable with one from Bernier et al. (2007), the time parameter is set to 200 days and permeability is converted into hydraulic conductivity which can be determined by using formula below:

$$K = k\frac{\rho g}{\mu}$$

where K is hydraulic conductivity, k is permeability, ρ is density of water (1000 kg/m^3), g is gravity acceleration (9.8 m/s^2) and μ is dynamic viscosity of water (8.9E-4 Pa.s). Result of preheated specimen at 50°C (blue line) is chosen as it gives the simplest graph interpretation during period of 200 days of experiment. Based on the graph, permeability at the beginning of the test is 1E-18 m^2 and in the 200th day the value decreased to 1E-19 m^2. Thus, the evolution of hydraulic conductivity can be estimated and the result shows it decreased 1 order of magnitude during the first 200 days. The result is depicted under table below.

Table 2. Result of conversion from permeability to hydraulic conductivity

Parameters	Day 0	Day 200
Permeability k (m^2)	1E-18	1E-19
Hydraulic conductivity K (m/s)	**1.10E-11**	**1.10E-12**

Even though both experimental results are similar, there are some points to note which might lead to a different result of experiment. First, Zhang (2018) used pre-heated specimens while Bernier et al. (2007) used non-heated one. The temperature might affect to the cracks intensity which then affect to the sealing rate. We expect that the crack intensity in preheated sample might be higher than non-heated one since the preheated specimen tends to have a lower water content, making the clay prone to shrinking which further induces cracks. Second, different confining pressure during experiment also might affect the sealing rate. Under a higher confining pressure, the sealing rate induced by hydraulic loading might be slower due to lack of water in between cracks, thus reducing the capability of clay to expand and seal the crack. Third, there was not enough data related to property of healed part, thus it is premature to state Boom clay has total self-healing capability. The full picture can be obtained with additional data (i.e. strength of healed part) and compare it with initial one.

Thermal Aspect

Not only from the Hydraulic Aspect, self-sealing mechanism can also be analyzed from the aspect of thermal change. The observed mechanisms are volumetric expansion of specimens and evolution of hydraulic conductivity through time due to the change of temperature. For expansion, the inspection was determined by two ways: 1) visual monitoring of cracks for one-year period and 2) examining the change of swelling pressure while increasing and decreasing temperature under certain confining stresses. For hydraulic conductivity, the inspection was held by flowing water through the specimens while increasing temperature in certain amount of time and the evolution of hydraulic conductivity was monitored.

Result showed that clay expands during thermal increase and shrinks during thermal decrease. This is proofed by one experiment from Hedan et al. (2014) which monitored the evolution of cracks width during 1 year period which cover both winter and summer time (depicted in Fig 11). Rising temperature in summer increased relative humidity (black line) which then resulted for clay mineral to swell and reduced the discontinuity distance (grey line). This can be explained by higher amount of water particle in the air during summer increased the possibility to have a contact with clay particle, which then resulted to swelling of clay mineral and leads to the sealing mechanism. On the contrary, decreasing temperature in wintertime influenced the air molecule to lose its capability to hold more water particle, thus relative humidity decreased and leaded cracks to reopen. Based on this experiment, it can be concluded that temperature gave undirect effect to the sealing mechanism, in this case it occurs through evolution of relative humidity. Full scheme of the process is depicted in Fig 12.

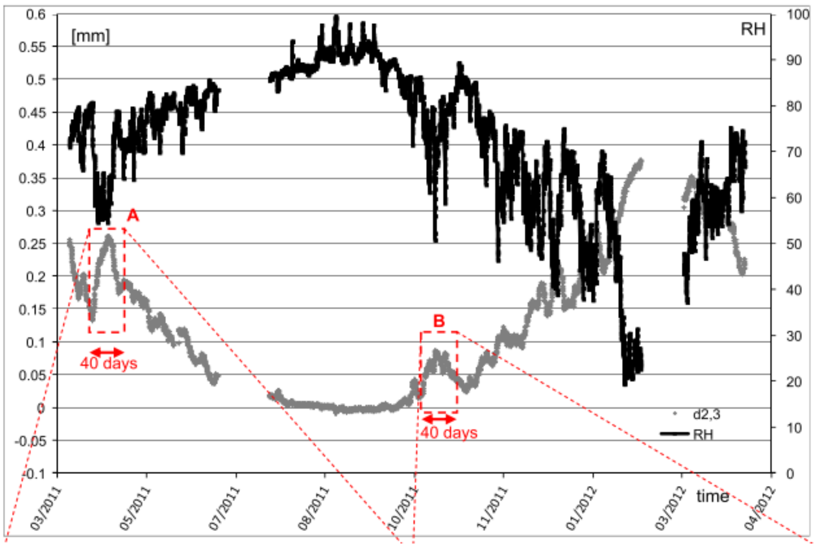

Fig 11. Cycle of RH (black line) and discontinuity displacement (grey line) in 1 year

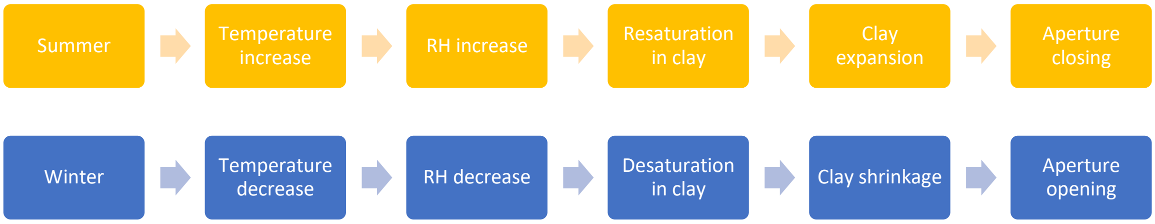

Fig 12. Full scheme of aperture closing and opening for summer and winter

Another similar result came from experiment by Zhang et al. (2017) which indicated a swelling mechanism of Callovo-Oxfordian clay (COX) under increasing temperature. The test was held by heating and cooling the specimen under several isostatic stress. However, an interesting remark is the specimen started to contract after the temperature was raised from 56 °C to 68 °C after before it expanded during heating process from 23 °C to 56 °C (Fig 13). This might occur as the effect from not utilizing flowing water thus at some heating point the water content was dropped and the sample shrinked then contracted.

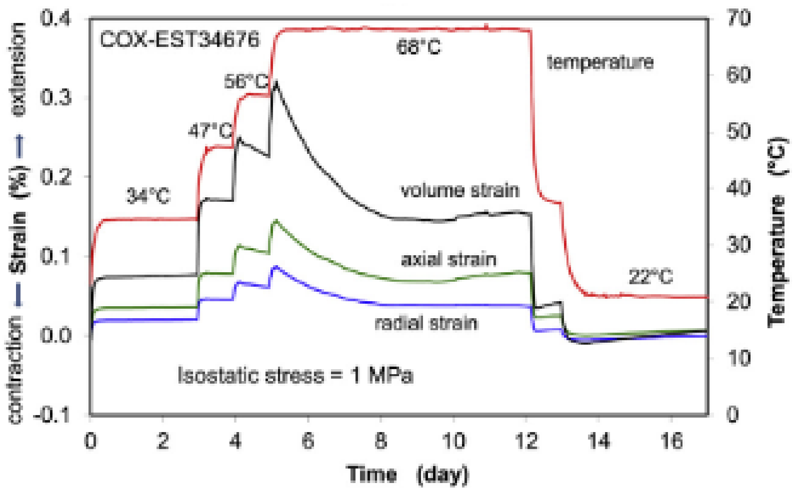

Fig 13. Thermal expansion of COX during heating from Zhang et al. (2017)

Result for hydraulic conductivity evolution shows a different outcome. Observation result from Zhang et al. (2017) stated that permeability was not significantly affected during heating and cooling cycle between 20 °C and 90 °C (Fig 14). They stated the sealing rate was even higher when the temperature below 20 °C, then it went slower after being heated. On the contrary, result from Cho et al. (2000) showed a rise of hydraulic conductivity during temperature increase even though it was not significant (Fig 15). The differences between the results are yet to be observed.

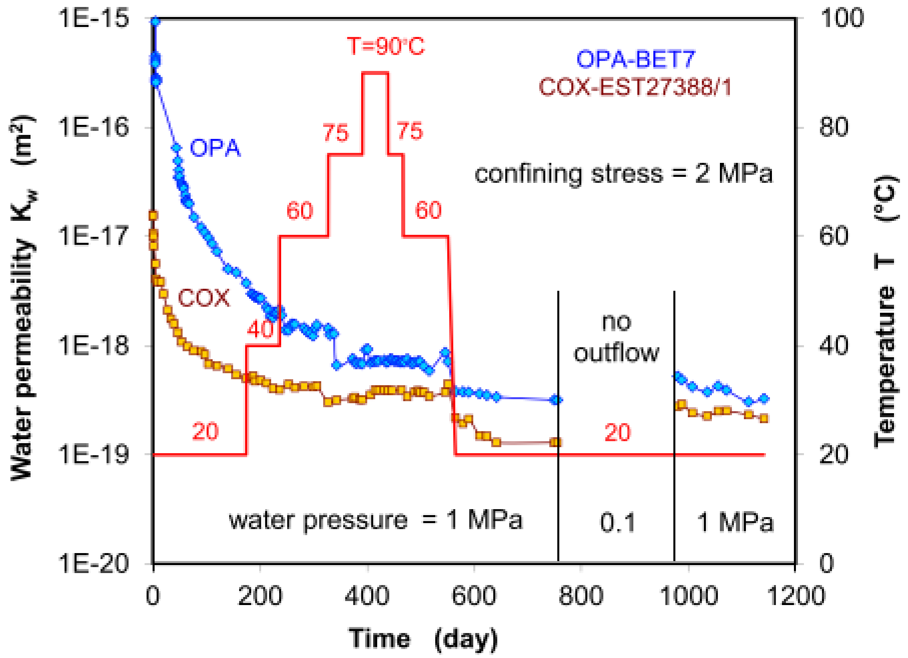

Fig 14. Permeability evolution of COX and OPA sample during heating and cooling from Zhang et al. (2017)

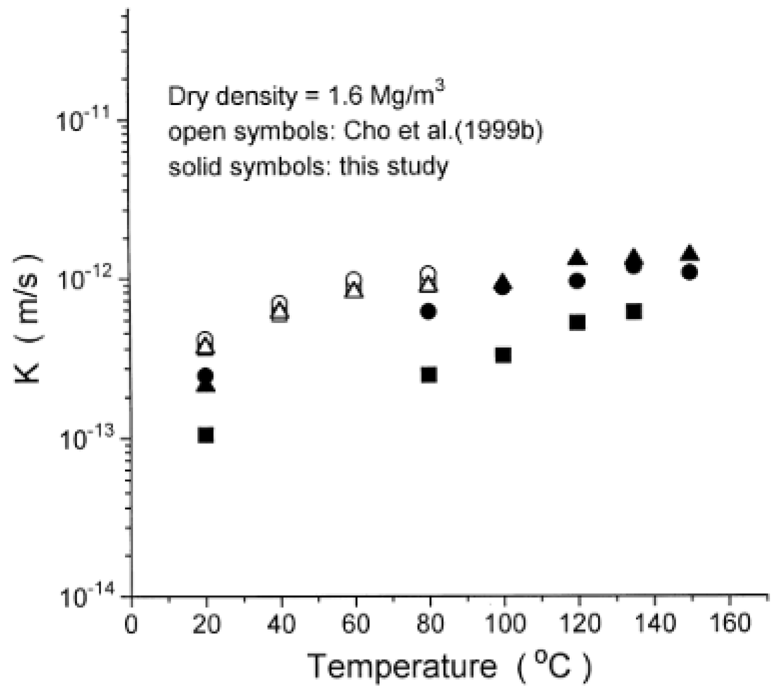

Fig 15. Permeability evolution of COX and OPA sample during heating and cooling from Cho et al. (2000)

Chemical Aspect

Self-sealing mechanism can also be affected chemically. The assessment of such aspect was held by reacting the clay specimens to different level of pH and salinity. For pH, the assessment consists of two ways: 1) reacting clay with cement water solutions with high pH and 2) injecting fluid chemistry into artificially cracked clay specimens. For salinity, experiment incorporates reaction between clay and NaCl saturated water.

An equal result is obtained for salinity field. Experiment from Bernier et al. (2007) shows a lower sealing rate of Opalinus clay under high salinity environment. Similar result related to the lower swelling strain in high-salinity fluid is also shown from Hauber et al. (2005) where they compared reaction for clay rocks and marls with distilled water and NaCl-saturated water. Lower swelling strain would affect to the lower swelling rate, thus affected to the lower sealing rate. Such condition might appear due to the reduction of osmosis process between clay particles as the effect of additional ion in high-salinity water thus hinders water absorption in between clay particles.

While salinity field shows an equivalent result, test in pH field shows a conflicting outcome. One experiment from Bernier et al. (2007) inspected sealing rate for Opalinus clay and Boom clay. Result shows that specimens tested with alkaline fluid (high pH) experienced a faster sealing rate compare to the non-alkaline fluid. On the other hand, geochemical modelling from Honty et al. (2010) showed a contrary result. The experiment was held to model the interaction between Boom clay and concrete as the disposal place for high-level radioactive waste. A model was generated to predict relative stability of primary minerals in Boom Clay under condition of mixed with cement-water solution with high pH. The result is depicted under Fig 16. There are several minerals observed but the highlight is the decreasing amount of clay minerals which is represented by kaolinite, illite and montmorillonite-Na (inside red circle) under an increasing pH solution. Montmorillonite-Na mineral belongs to the smectite group which has the ability to swell and shrink, as mentioned in the Clay Minerals section. This degradation also affect to the decrease of cation exchange capability, thus would decrease the capability of clay to swell and shrink which then decreases the self-sealing capacity.

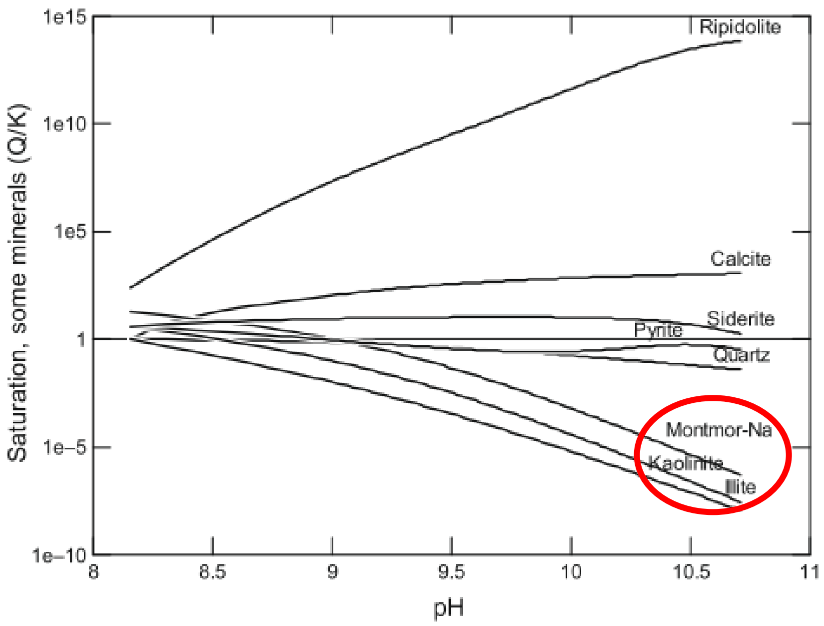

Fig 16. Degradation of clay mineral (kaolinite, illite and Na-montmorillonite) under high pH reaction from Honty et al. (2010)

There are several points to note based on the above experimental result. First, contradictive results in pH field should be re-examined. This might occur due to the different usage of solution. By using cement-water solution in the experiment from Honty et al. (2010), the reaction with Boom Clay can be disturbed since the solution might contain unwanted substance. As an addition, there is no further elaboration such as plot of graph which could support the finding from Bernier et al. (2007)'s experiment. Second, result from the salinity field indicated an indirect relation, since Bernier et al. (2007) presented sealing rate data while Hauber et al. (2005) provided swelling strain data. Even though sealing rate can be derived from swelling strain data, it would be more accurate and representable to compare the results with the same parameters.

Mechanical Aspect

Lastly, we indicate that mechanical aspects of clay might affects its self-sealing attribute. The experiment consists of increasing confining stress of artificially cracked clay specimen while monitoring evolution of permeability or hydraulic conductivity.

In term of interaction between mechanical and chemical aspect, one experiment from Bernier et al. (2007) inspected sealing process of artificially cracked Opalinus clay under increasing confining stress while applying axial hydraulic conductivity of alkaline fluid and high salinity water. The result is shown under Fig 17. It can be seen that hydraulic conductivity which denoted as K_{in} and K_{out} decreased while confining stress which denoted as P_{con} increased. Both mean pore water pressure and effective stress were adjusted to keep Kin and Kout balance.

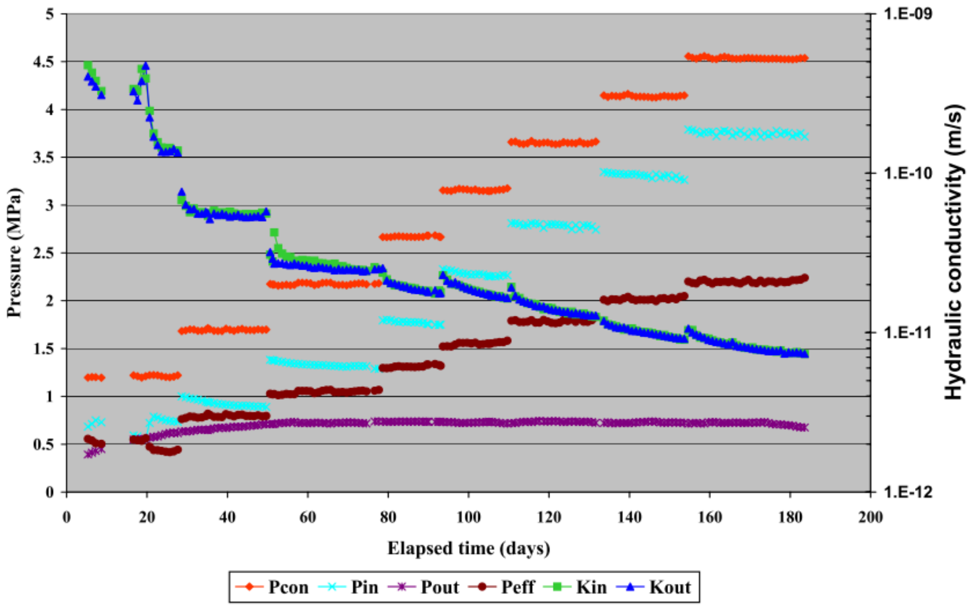

Fig 17. Decreasing hydraulic conductivity of Opalinus clay (Bernier et al., 2007)

Another experiment from Zhang (2013) inspected sealing mechanism of Opalinus clay (OPA) under compression. The observation included a monitoring of two samples with different size which inserted in the cell test and compressed by increasing axial and radial stresses. The change of permeability was measured by injecting nitrogen gas through the specimen and the outflow is monitored. The result is depicted under Fig 18. It can be seen from the graph that permeability decreased along with the increase of compression (represented as normal stress σ_n). Large sample had a higher initial permeability than small one due to different intensities of the fractures. However, both specimens experienced similar sealing rate as a function of increasing normal stress.

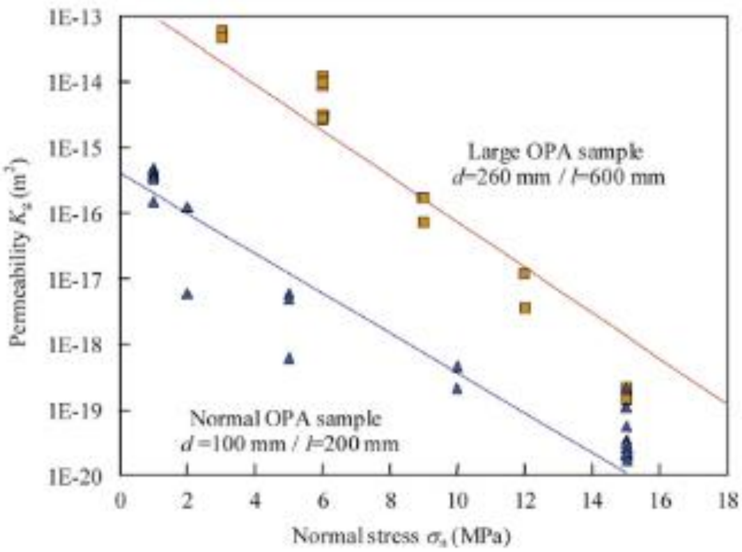

Fig 18. Decreasing permeability under increasing normal stressof OPA sample from Zhang (2013)

Based on the results above, it can be concluded that both experiments showed a sealing mechanism under a higher confining stress. However, there are several points to note. First, experiment from Bernier et al. (2007) utilized alkaline fluid and high salinity solution while one from Zhang (2013) used nitrogen gas to monitor sealing rate. This might affect to the final hydraulic conductivity or permeability due to the differences in fluid properties. Second, even though both results show a decreasing trend of flow, result from Zhang et al. (2013) was not performed under a time function. Thus, we expect for a more detailed depiction of permeability evolution if time is taken into consideration.

Conclusion

Based on data above, we conclude that clay experiences self-sealing mechanism. Such mechanism is mainly induced by water absorption from clay mineral, specifically from smectite and vermiculite group which has the capability to swell and shrink. Sealing mechanism increased under influence of low salinity environment, flowing water, increasing relative humidity and higher confining stress while more data is needed to inspect the effect of temperature and pH as they gave a contradictive result to the mechanism. In addition, more comprehensive experiment is required to be able to quantify the healing mechanism in clay.

3. Material Description: Concrete

3.1. Structure and Description

Concrete has become a part of man-made structure since long time ago. It is believed that the Egyptians were the first to utilize the early form of concrete by mixing mud and straw to form bricks and utilize lime and gypsum to make mortars in around 3000 BC. Then, the advance development came from the Romans where they used calcined limestone mixed with lime and water with addition of aggregates such as brick, broken tiles, and crushed stone in around 70 AD. The next advancement in the early 19th century was the invention of Portland cement which was prepared by mixing clay and limestone in the heating system until CO_2 is diminished. Such substance gives a better performance as a bonding material in concrete.

In terms of composition, concrete mainly consists of aggregates, water and binder. Based on definition from Urschel Iii and Judd (1977) and Mignon et al. (2015); Urschel Iii and Judd (1977), concrete is a blend of Portland cement, fine and coarse aggregate, and water. Portland cement is not the only cement type, nevertheless it is the most common type of cement which can be used as mixing material. Additive can be added to the mixture to modify the desired properties and characteristic of concrete. This additive is whether to stimulate or hinder the reactions of the mixture. Example of this additive is silica and alumina which contain material known as pozzolana. The substance reacts with lime under wet condition to establish cementitious material.

3.2. Self-sealing and self-healing mechanisms

One of the distinctive characteristics of concrete is self-healing and self-sealing capability. Different from the mechanism in clay which is induced by water adsorption and swelling, sealing and healing in concrete is mainly generated by further hydration of the un-hydrated cement. Such process then induces the closure of discontinuity and reduction of permeability. Next subchapters will discuss various aspects controlling sealing and healing mechanism such as cement hydration and re-hydration, calcium carbonate precipitation, and other mechanisms.

Cement, Hydration, and Re-Hydration

As mentioned above, cement is one of the constituent materials of concrete. Cement is defined as a material composed of lime with adhesive and cohesive properties which make it capable to bond mineral fragments into compact whole (Neville, 1995). The bonding capability will occur under the form of water-cement paste in which defined as *cement hydration*. During the hydration process, cement experiences several stages which depicted under Fig 19. It can be seen the main product of hydration reaction consist of solid product of hydration and gel water. A fully hydrated cement, as depicted in the right part of Fig 19, can be achieved as suggested by Power (1949) by utilizing cement particle with the size of less than 50 µm and grinded continuously under water for five days.

One factor which controls cement hydration rate is fineness degree of cement. Finer cement particles will give a more evenly mixture as it generates a faster rate of hydration. In other word, there will be a higher percentage of un-hydrated part in coarse cement than the fine one under the same amount of time. In addition to the faster rate of hydration, utilizing fine particle of cement would improve the strength development. The more cement particle being hydrated, the more solid products of hydration will be generated thus it increases the strength of concrete. In other words, strength development is slower when utilizing coarser cement.

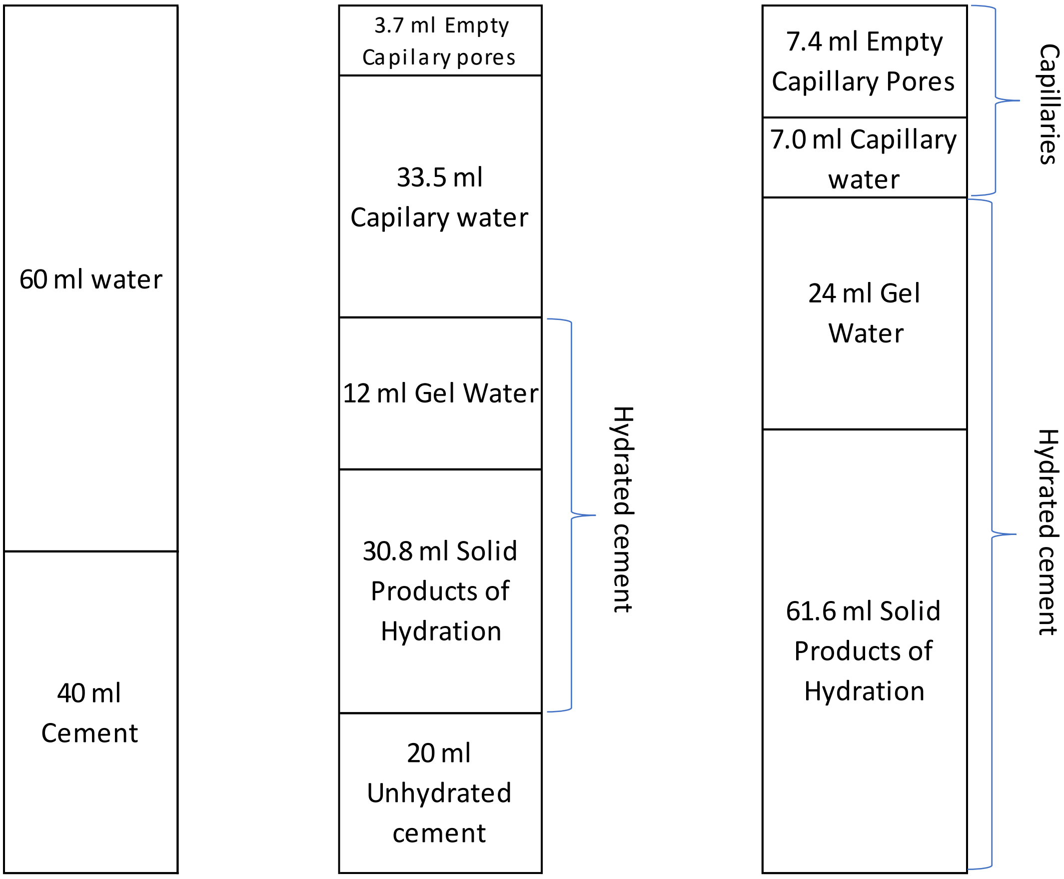

Fig 19. Cement paste hydration at 0% hydration (left), 50% hydration (middle), and 100% hydration (right) from Neville (1995)

In terms of chemical composition, there are 4 main compounds in cement: Tricalcium silicate C_3S, dicalcium silicate C_2S, tricalcium aluminate C_3A and tetracalcium aluminoferite C_4AF (Table 2). In reaction with water, cement will generate different products which depend on each compound. Amongst of cement compounds, hydration of both C_3S and C_2S contributes more to concrete strength. The chemical reactions for both compounds are depicted under Reaction 1 and 2. C_3A hydration has unique characteristic where it behaves very violent and triggers sudden stiffening of cement paste. To reduce the effect, gypsum is added to the mixing ingredient. For tetracalcium aluminoferite C_4AF is believed to hydrate into tricalcium aluminate hydrate.

Table 2. Main compounds of Portland Cement from Neville (1995)

Name of Compound	Oxide composition	Abbreviation
Tricalcium silicate	$3CaO.SiO_2$ or Ca_3SiO_5	C_3S
Dicalcium silicate	$2Cao.SiO_2$ or Ca_2SiO_4	C_2S
Tricalcium aluminate	$3CaO.Al_2O_3$ or $Ca_3Al_2O_6$	C_3A
Tetracalcium aluminoferite	$4CaO.Al_2O_3.Fe_2O_3$ or $Ca_4Al_2Fe_2O_{10}$	C_4AF

$$2Ca_3SiO_5 + 7H_2O \rightarrow 3CaO.2SiO_2.4H2O + 3Ca(OH)_2 + heat \qquad (1)$$

$$2Ca_2SiO_4 + 5H_2O \rightarrow 3CaO.2SiO_2.4H_2O + Ca(OH)_2 + heat \qquad (2)$$

During hydration process, however, there will always a small amount of cement which left unhydrated. This unhydrated part will induce a sealing and healing mechanism once it is rehydrated by water which infiltrate through the cracks in the concrete body. This further hydration mechanism then strengthens the microstructure of concrete body.

Calcium carbonate precipitation

Other than cement rehydration, sealing and healing of concrete might be induced by precipitation of calcium carbonate. As written in chemical reaction 1 and 2 above, cement hydration produces several new compounds, one of which is calcium hydroxide ($Ca(OH)_2$). When contact with carbon dioxide (which dissolved in water), such compound produces calcium carbonate and water. The chemical reaction is written in the Reaction 3. Then, this newly formed calcium carbonate is precipitated and accumulated in between concrete cracks, thus decreases discontinuity gaps and reduce water flow. The condition is depicted under Fig 20. This mechanism has been inspected by several researchers such as Edvardsen (1999), Neville (2002) and (Edvardsen, 1999); Mihashi and Nishiwaki (2012); (Neville, 2002).

$$CO_2 + Ca(OH)_2 \rightarrow CaCO_3 + H_2O \qquad (3)$$

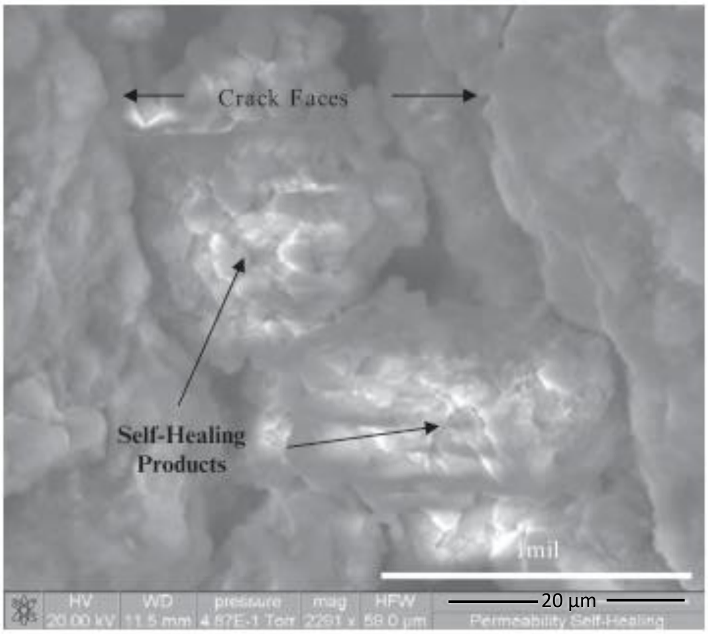

Fig 20. Self-healing product from Environmental Scanning Electron Microscope from Li and Yang (2007)

Other Mechanisms

Other than two mechanisms mentioned above, self-sealing and self-healing mechanism can be designed by involving additional substance to the concrete mix. Since concrete is a man-made material, the properties can be adjusted to induce sealing and healing mechanism. For instance, the addition of water-swelling rubber particle to cementitious material has been inspected by Lv et al. (2017); Mignon et al. (2015). The particles are activated when in contact with water which infiltrate through cracks in the concrete, then they swell, fill the cracks and reduce the hydraulic conductivity. Another research was held by Van Tittelboom et al. (2012) which inspected alternative binder material in concrete to extend obtainability of un-hydrated element for future self-sealing and self-healing capability. These experiments make concrete has more possibilities to have other type of healing or sealing mechanisms than clay.

3.3. Experimental Observations

This subchapter discusses various experimental results for self-sealing and self-healing in concrete. In contrast to clay which rather have more in-situ experiments, most of concrete investigations are conducted in the laboratory. The discussion is presented under four different aspects such as Hydraulic Aspect, Thermal Aspect, Chemical Aspect and Mechanical Aspect which affect the self-sealing and self-healing mechanism.

Hydraulic Aspect

This section discusses self-sealing and self-healing mechanism of concrete under influence of hydraulic loads. The objective is to determine the effect of water to the sealing and healing mechanism. The experiments consist of sample submersion under water and monitoring evolution of water flow through a cracked specimen in certain amount of time. For healing mechanism, dynamic modulus measurement was held to inspect the initial and final resonant frequency of specimens.

One experiment was held by Li and Yang (2007). The test examined sealing and healing mechanism under various conditioning regimes (CR) related to hydraulic aspect. CR1 simulated outdoor environment as in rainy and unclouded days, CR3 simulated water permeation through cracks in concrete and CR5 simulated water submersion of concrete as in underwater structures. The summary of CRs is written under Table 3 below.

Table 3. Summary of conditioning regimes of the experiment which adapted from Li and Yang (2007)

Conditioning regimes	Environment	Model	Temperature (°C)
CR1	Water-air cycle	Outdoor environment (i.e. rainy and unclouded days)	Water: 20 Air: 21 ± 1
CR3	Water permeation	Continuous contact with water with hydraulic gradient	20
CR5	Water submersion	Underwater structure	20

Dynamic modulus measurement was held to observe crack recovery. The test consisted of resonant frequency measurement of specimens before and after CR1 conditioning. Result showed the sample experienced a full recovery for < 50 µm crack width, partial recovery for 50-150 µm crack width and no recovery recorded for > 150 µm crack width. Permeability test also showed a similar result. After 10 wet-dry cycles, full recovery of sample was achieved from the specimen with < 50 µm crack width while partial or no recovery was achieved from one with > 150 µm crack width. This shows that both sealing and healing capability decreases for increasing crack width. The results of both tests are depicted under Fig 21.

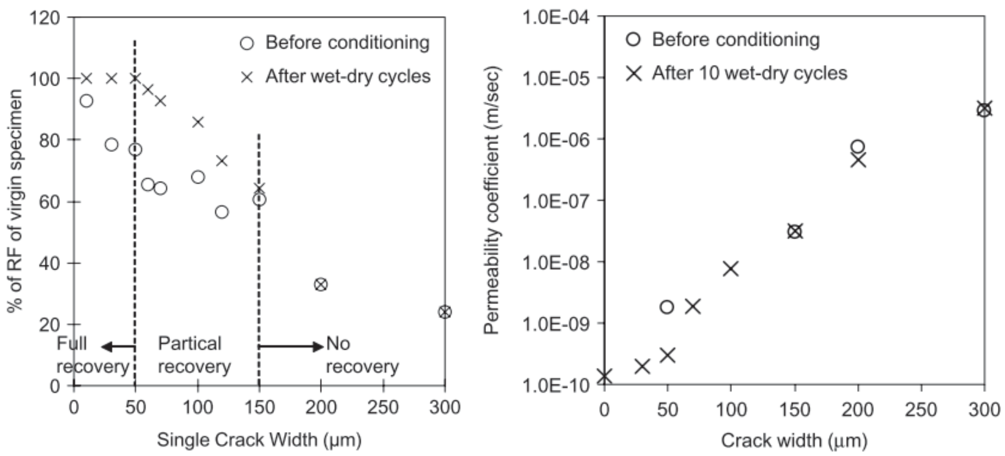

Fig 21. Result of resonant frequency test (left) and permeability test (right) from Li and Yang (2007)

To inspect the influence of waterflow and water submersion to sealing and healing process, CR3 and CR5 conditioning regime were held. The samples were preloaded to 1.5%, 2% and 3% of strain then submerged for 14 days (CR5). Then the specimen flowed with water and the evolution of permeability was observed (CR3). Full scheme is depicted under Fig 22. The result showed a decreasing permeability within 3 days of permeation and continued asymptotically as depicted under Fig 23. However, there was no visual sign for healing mechanism during 14 days of water submersion. Similar condition also applied to the partial submersion where crack healing was only found near the water surface but not below the water surface.

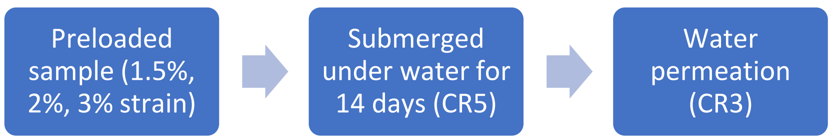

Fig 22. Scheme of water permeability experiment

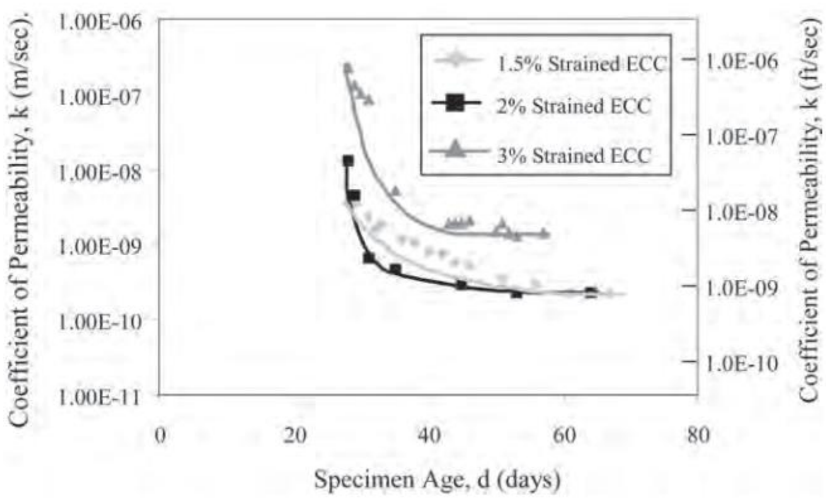

Fig 23. Result of permeability test for three different strain sample from Li and Yang (2007)

Another similar experiment was held by Reinhardt and Jooss (2003) which inspected effect of sealing mechanism with flowing water. The specimens were artificially cracked into various widths of 0.05 mm, 0.10 mm and 0.15 mm then flowed with water under ambient temperature of 20 °C. Result showed flow rate in the first 100th hours decreased to approximately 65% from the initial value. Another finding is that the flow rate decreases along with the crack width. Such result is a logical condition as the lower quantity of water flow through the narrow discontinuity than the wider one. The experimental result is depicted under Fig 24.

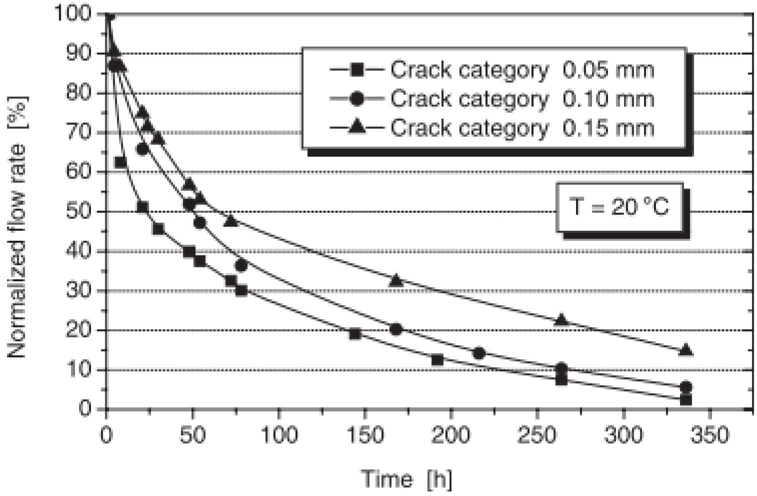

Fig 24. Result of permeability test under temperature 20 °C from Reinhardt and Jooss (2003)

There are some points to note regarding the hydraulic aspect. First, both experimental result from Li and Yang (2007) and Reinhardt and Jooss (2003) shows a sealing mechanism in the concrete specimen. Even though there is a difference of flow unit used between both experiments, the results show a decreasing flow rate or hydraulic conductivity under influence of flowing water in the same temperature (20 °C) in certain amount of time. Another finding is Li and Yang (2007) used strain parameter which gave no information related to crack condition. It might be more representable if the test also inspected the outcome to the crack dimension. Second, the absent of healing mechanism in CR5 environment from Li and Yang (2007) is rather contrary to the principle theory of cement hydration. Based on the chemical reaction (1) and (2), cement hydration process only requires H_20. Thus, flow or no flow should not be a hindrance for concrete to have sealing or healing mechanism as long as H_20 is still available. Third, it will be more representable if the result of submerged specimen from CR5 condition was also tested with dynamic modulus measurement to inspect whether any healing effect or not. By applying this test, the result would be more reliable and could be quantified.

Thermal Aspect

This section discusses the relation of sealing and healing mechanism under influence of thermal change. The inspections included observations of flow evolution and strength inspection of specimens under increasing temperatures.

One experiment was held by Reinhardt and Jooss (2003) which inspected the influence of increasing temperature to the sealing rate. The test setup was equal with their experiment in Hydraulic Aspect except for the increased of ambient temperature to 50 °C and 80 °C. The result showed the average flow rate in the first 100^{th} hours decreased up to 80% and 85% from the initial value for temperature level of 50 °C and 80 °C respectively. The graph is presented under Fig 25. It can be seen from the graph that the slope is much steeper for the higher temperature. Such result shows increasing temperature of 30 °C clearly affect to the increase of sealing rate up to 5%. Another finding is that wider crack width gives a higher normalized flow rate compare to one with narrower crack width in the same amount of time.

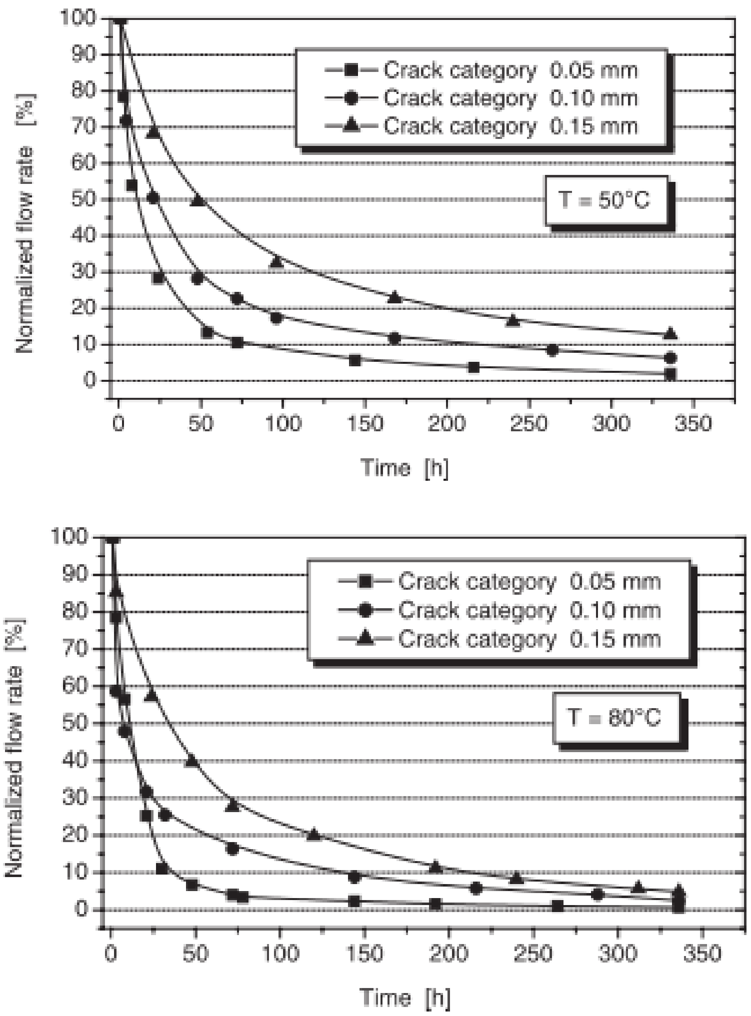

Fig 25. Result of permeability test under temperature 50 °C (above) and 80 °C (below) from Reinhardt and Jooss (2003)

Another experiment was held by Li and Yang (2007) which inspected the influence of thermal increase to healing mechanism. Test setup was similar to their experiment in Hydraulic Aspect (CR1) except for the additional variable of increasing temperature. This new environment was called Conditioning Regime 2 (CR2). The experiment simulated outdoor environment which incorporated the cycle of water-air with the increase of temperature up to 55 °C by oven-dry the specimen. The summary of the experiment is depicted under Table 4. First, the sample was preloaded up to predetermined strain levels ranging from 0.3% to 3%. After unloading, the sample was subjected to 10 wet-dry cycle of CR1 and CR2, then uniaxial tensile test was held for healed specimens from both CR2 and CR3 and the result was compared to each other.

Table 4. Summary of Conditioning Regimes 2 experiment from Li and Yang (2007)

Conditioning regimes	Environment	Model	Temperature (°C)
CR2	Water/hot air cycle	Cyclic outdoor environment with high temperature	Water: 20 Oven: 55 Air: 21 ± 1

The result is shown under Fig 26. It can be seen that reloading curves for the specimen under CR1 condition (left picture) show a considerably lower stress level compare to preloading one. A significant difference is shown under CR2 condition (right picture) where reloading curves have higher stress level up to 1 MPa compare to the pre-loading. Such condition clearly shows that temperature plays a significant role for healing mechanism where in this case is represented by the strength increase. The strength improvement might be comparable with the steam curing process of concrete where the increasing temperature also escalating the hydration process and create a stronger bond between cement particles.

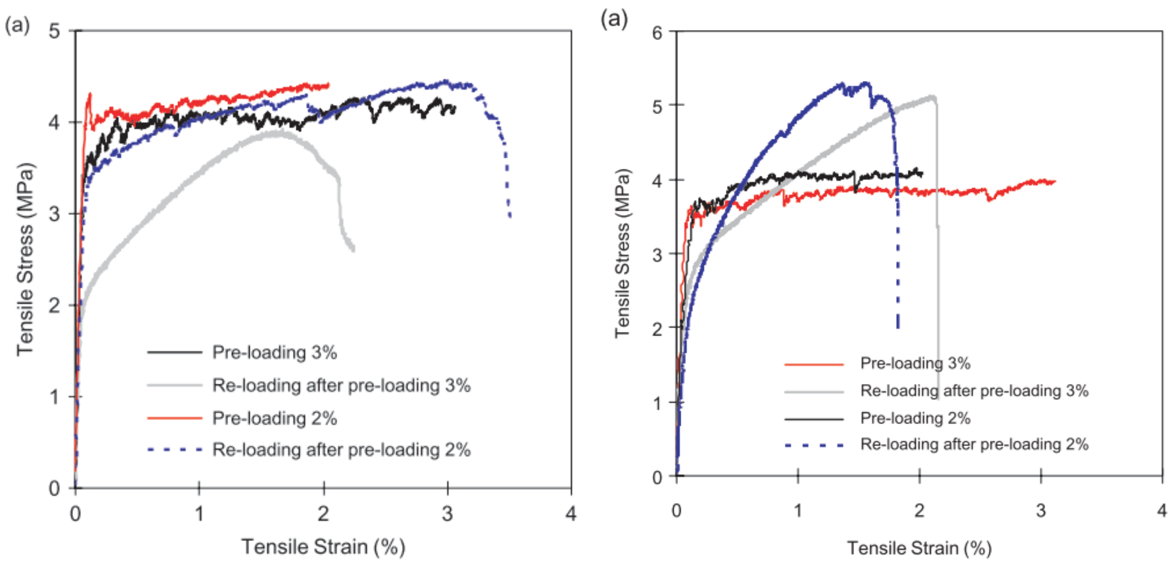

Fig 26. Pre loading and reloading of CR1 (left) and CR2 (right). Ultimate tensile strength is higher under CR2 condition. Source: Li and Yang (2007)

There are some points to note for this aspect. First, increasing temperature affects to the improvement of both sealing and healing mechanism which represented by a faster sealing rate and a higher strength respectivelly. However, there was no inspection for sealing mechanism in CR2 condition from Li and Yang (2007) and no inspection for healing mechanism for Reinhardt and Jooss (2003). A further inspections are needed to have a more extensive comparison for both sealing and healing mechanism. Second, Reinhardt and Jooss (2003) utilized the climatic chamber for the temperature increase where the test cells were put while Li and Yang (2007) utilized oven-dry method. This condition might give a different outcome considering both results are obtained from different method and device.

Chemical Aspect

This section discusses sealing and healing mechanism under influence of chemical aspect. The tests include the inspection of different salinity and pH condition and their effect to sealing and healing mechanism.

One experiment was held by Li and Yang (2007) which involved the inspection of sealing and healing mechanism in concrete under high salt environment. The objective was to determine the effect of high salt environment to sealing and healing mechanism. The experiment consisted of comparison of diffusion coefficient between concrete and mortar. Both specimens were cracked with predetermined deformations level then they were submerged in NaCl solution while the diffusion coefficient is monitored.

Result showed diffusion coefficient of concrete increased linearly along with the deformation while mortar had an exponential increase started from 0.5 mm deformation. The significant difference occurred due to higher crack intensity in mortar thus the diffusion of NaCl solution into the specimen was higher. However, NaCl solution was proofed to have a contribution to the sealing and healing mechanism. This can be seen from the accumulation of salt deposition in the healed part of specimen which closing the gap and sealed the crack. The result is depicted under Fig 27 and Fig 28.

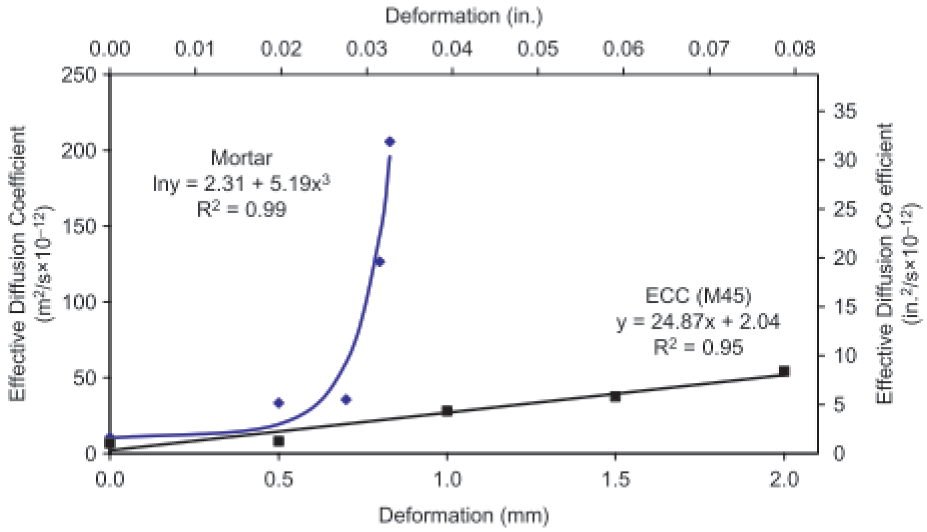

Fig 27. Result of effective diffusion coefficient of mortar and concrete from Li and Yang (2007).

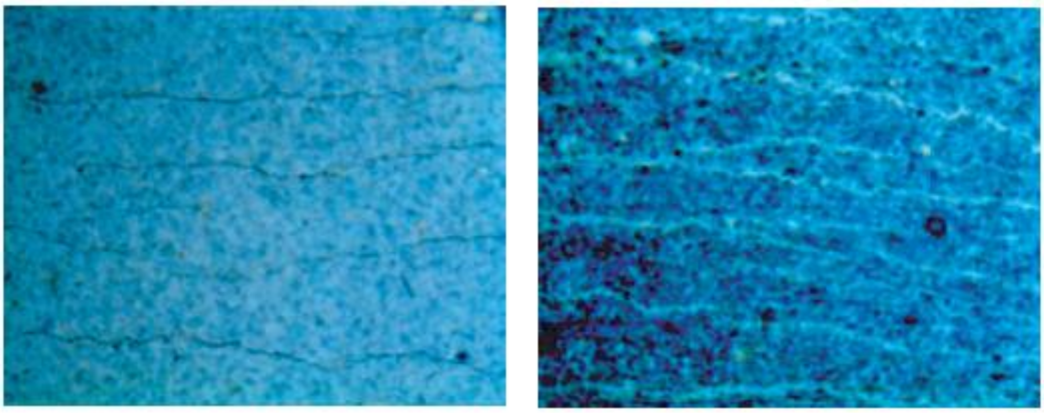

Fig 28. Sample condition before (left) and after (right) the submersion in NaCl solution. White parts in the right picture are the healed material with the deposition of salt. Source: Li and Yang (2007).

Another test which inspected healing mechanism was held by Wang et al. (2014). The main objective of the experiment was inspecting self-healing mechanism of concrete by utilizing microencapsulated bacteria. The test consisted of the observation for several type of concretes, two of which were the inspection of regular concrete and concrete with additional nutrient for bio-precipitation. The nutrient consisted of yeast extract, urea and calcium nitrate tetrahydrate ($Ca(NO_3)_2.4H_2O$). Both samples were tested under four different environments: immersed under regular water, wet-dry cycles with water, immersed under deposition medium (DM) and wet-dry cycles with DM. Ingredients of DM were composed of 0.2 M urea and 0.2 M $Ca(NO_3)_2$.

Result of experiment is shown under Table 5. An interesting result comes from the fact that healing result of sample with nutrient under 'in water' condition was higher than the sample with nutrient under 'in DM' condition. As written above, both nutrient and DM consist of calcium nitrate ($Ca(NO_3)_2$) where such compound plays an important role of calcium carbonate ($CaCO_3$) precipitation for sealing and healing mechanism in concrete. Precipitation of $CaCO_3$ depends on amount of CO_3^{2-} and dissolved Ca^{2+} which corelated to some factors such as: concentration of CO_2, ambient pH and composition of concrete matrix. Source of Ca^{2+} can be obtained from $Ca(NO_3)_2$, $Ca(OH)_2$ and unhydrated cement particles. Based on that information, one can conclude that sample with nutrient which tested under 'DM condition' should have the highest healing rate due to the abundant source of Ca^{2+}, but the result showed a different outcome. Such condition occurs due to the fact that $CaCO_3$ precipitation was also controlled by ambient pH where a higher pH is preferable for $CaCo_3$ precipitation. Since water has a higher pH than DM, thus $CaCO_3$ precipitation in water is higher than one with DM which resulted to the higher healing rate.

Table 5. Result of healed specimen from Wang et al. (2014)

Environments	With Nutrient	Regular
In water	47%	30%
Wet-dry cycle in water	38%	18%
In DM	25%	34%
Wet-dry cycle in DM	38%	46%

Another similar result was obtained by the test from Mignon et al. (2015) whose inspected superabsorbent polymers (SAP) as a potential additive to concrete for sealing and healing capability. The aim of the test was to determine the effect of pH to the swelling capability of SAP. The experiment was held by incubated SAP under various pH environment ranging from 1 to 13. In general, the result showed an increasing swelling capacity along with the increasing pH as shown under Fig 29. From the graph it can be seen the swelling capacity of sample 1 is relatively higher than sample 2 and 3. This is due to the low concentration of cross-linking agent N,N'-methylenebisacrylamide (MBA) in sample 1 which affect to the swelling capacity of specimen. An interesting finding was the swelling capacity dropped significantly for pH higher than 12. This occurred due to the degradation of network integrity of the polymer in high pH environment thus SAP structure is disintegrated.

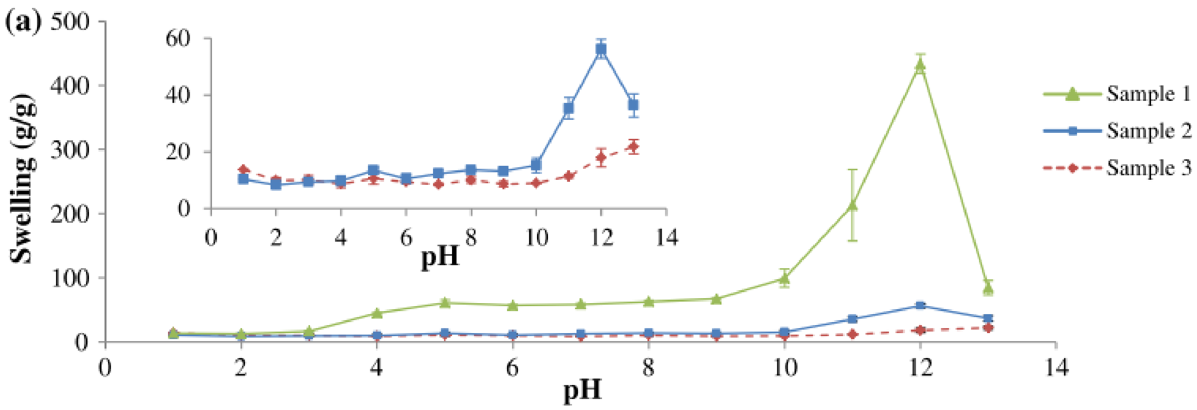

Fig 29. Result of increasing swelling capacity under higher pH environment from Mignon et al. (2015)

There are several points to note for chemical aspect. First, high salinity environment has a little contribution to the healing mechanism as further hydration still plays a bigger role to such environment. Further references and study are needed to quantify the portion between NaCl precipitation and further hydration product for healing mechanism. Second, comparison between mortar and concrete from Li and Yang (2007) experiment is not comparable to each other considering the crack intensity in mortar was much higher compare to concrete thus made the diffusion coefficient increased exponentially. It would be more suitable if the comparison was held between the materials which have similar crack intensity then tested to determine their sealing and healing mechanism. Third, higher pH environment have a clear effect to the improvement of healing rate of concrete with additional nutrient and swelling capacity of superabsorbent polymer. However, additional tests for both materials should be conducted to strengthen the statement.

Mechanical Aspect

This section describes the contribution of mechanical loading to sealing and healing mechanism in concrete. The tests include the inspection of permeability under and after loading. Experimental results which presented below are based on the paper from Hoseini et al. (2009) where they reviewed effect of mechanical stress on permeability of concrete from several researchers.

One experiment was conducted by Kermani (1991) which inspected the permeability of stressed concrete. First, the ultimate strength of specimen was determined, then new samples from the same mix were loaded up to 70% of ultimate strength. These new loaded specimens then tested for permeability observation. The result is depicted in Fig 30 which display three different concrete mix. However, our focus is to the 'ordinary concrete' mix which utilized ordinary Portland cement with no admixture. It can be seen from the graph the ordinary concrete specimen experiences a slight decrease of permeability up to 30% of ultimate strength (area under red circle). Such condition shows a sealing mechanism which induced by the closing of cracks in the sample due to stress increase.

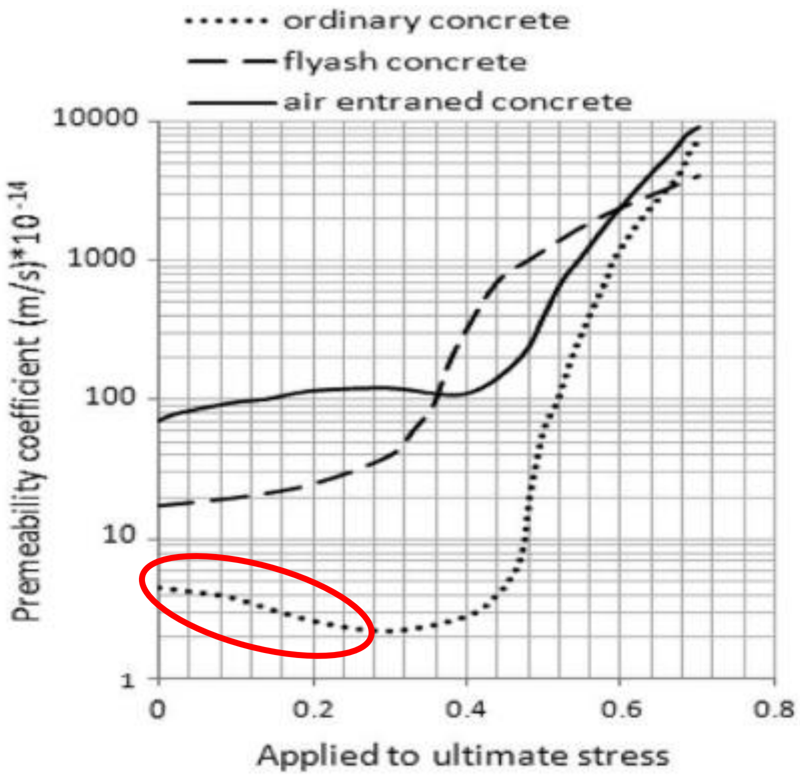

Fig 30. Effect of applied stress to the permeability from Kermani (1991)

Another experiment was conducted by Wang et al. (1997) which inspected the relation of permeability and crack opening displacement (COD) under loading and unloading condition. First, the samples were splitted into the range of distance from 25 µm to 550 µm, then permeability test was conducted under loading and after unloading. The result is depicted under Fig 31. It can be seen that in the same level of COD, sample under load experiences a lower permeability compares to one of after load. Such condition is induced by the closing distance of cracks under loading condition thus decreases the permeability.

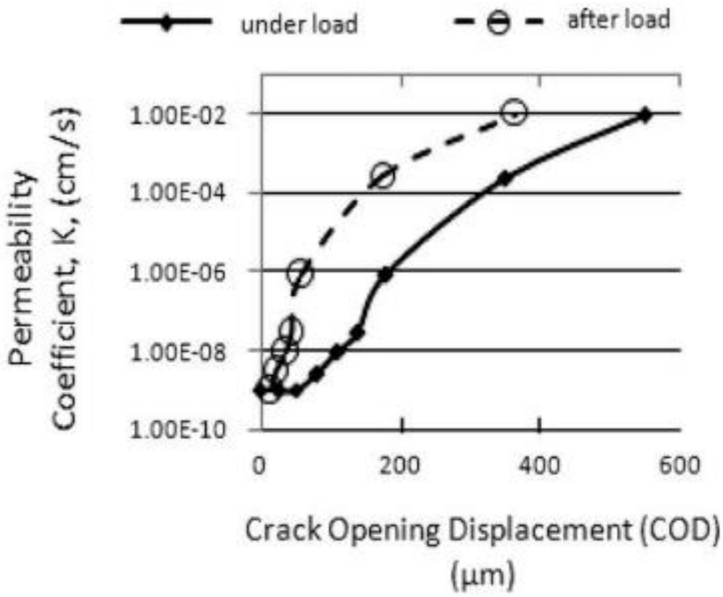

Fig 31. Permeability of specimen under load and after load from Wang et al. (1997)

There are several points to note related to the mechanical aspect to sealing mechanism. First, concrete experiences a decreasing permeability under a higher stress condition. The closing cracks and discontinuities might be the obvious cause to this sealing mechanism. However, both experiments did not discuss the further hydration of un-hydrated concrete as the alternative influence on the sealing mechanism. This information might give an additional insight of the portion between mechanical aspect and further hydration to the sealing mechanism in concrete. Second, result from Kermani (1991) shows that there is a certain maximum stress limit for concrete to the sealing mechanism before the permeability increase significantly due to coalescence of cracks in the specimen. Such condition might occur due to the brittle characteristic in the specimen which induced a higher cracks propagation when the sample is mechanically loaded. This is a valuable information if we want to inspect the similar behavior in clay.

Conclusions

Based on data presented above, we can conclude that concrete experiences sealing and healing mechanism under flowing water condition. However, more extensive study should be conducted to inspect such mechanism under fully submerged environment. An improved sealing mechanism is also shown under increasing temperature. From chemical aspect, high salinity gives little or no effect to the sealing mechanism while higher pH develops a greater result. A reducing permeability also occurs under increasing stress condition. More data should be held to observe the maximum limit of stress before the permeability starts to increase significantly.

4. Comparison Result and Discussion

This chapter contains comparison and highlight of experimental results between clay and concrete. The comparison is written based on the same aspects from the previous chapters: Hydraulic, Thermal, Chemical and Mechanical aspects.

4.1. Hydraulic Aspect

As discussed in two previous chapters, it can be concluded that water is a crucial component for self-healing and self-sealing process for clay and concrete. However, the mechanism for both materials are different. In clay, particle of water is needed to fill the interlayer space which then trigger the expansion and reduces discontinuity gap. Meanwhile in concrete water is needed to initiate further hydration of un-hydrated cement or to precipitate calcium carbonate ($CaCO_3$) which then induce the sealing and healing capacity.

Based on the experimental results, both clay and concrete experience sealing and healing mechanism under flowing water. In other words, hydraulic gradient plays an important role for both water particle adsorption in clay and further hydration in concrete. Another finding is the fact that there is no healing mechanism under fully submerged (CR5) environment for concrete, where such environment is considered comparable to the hydrostatic condition. However, there is no further investigation of hydrostatic condition for clay which make the statement is still open for discussion.

The contrary effect of flowing water and hydrostatic condition to the sealing and healing mechanism in concrete might develop another possible mechanism for sealing and healing which related to the particle clogging. When water is flowing through the specimen, friction force will be generated between flowing fluid and the soil skeleton (Verruijt and Van Baars, 2007). Such condition might develop the internal erosion in the specimen and the loose particle will be deposited in between the cracks which then close the gap and decrease hydraulic conductivity. Further experiment is needed to inspect this mechanism.

For healing mechanism inspection, there are different method used between clay and concrete. Dynamic modulus measurement is used in concrete while visual assessment is applied in clay. In principle, dynamic modulus measurement is a method which measure change of resonant frequency of specimens in the beginning of experiment (initial condition) and when test is complete (final condition). It is obvious that this method could give a better and more accurate quantification compare to the visual method. It can be concluded that such method could be applied for clay in order to obtain a quantifiable and reliable result of healing mechanism.

4.2. Thermal Aspect

Based on the experiments, it can be concluded that concrete experience a faster sealing rate and obtained an improved strength recovery under an increasing temperature condition while clay is not affected to such matter. Such mechanism might occur in concrete due to the condition which comparable to the steam curing process where cement hydration is enhanced by the increasing temperature. However, in spite of the absence of sealing mechanism, experimental result for clay showed an increasing volume due to heating. This is an interesting outcome considering sealing and healing mechanism in clay are induced by the swelling activity. Based on this discovery, it is needed to have additional references or more representable experiments to inspect temperature effect in clay.

Still related to the volumetric change, result stated that clay has the capability to swell and shrink under condition of climatic cycle (cycle of temperature and relative humidity) which covers both summer and winter time. Such condition occurs due to the swell-shrink capability which consider as the distinctive characteristic of clay which induced by the capacity of clay mineral to adsorb and release water particle. Meanwhile, there is no evidence for concrete to have such capacity. From the writer's perspective, it would be an interesting experiment to inspect the effect of cyclic temperature and relative humidity to the volumetric change of concrete for 1-year period.

4.3. Chemical Aspect

In terms of chemical aspect, concrete shows a faster sealing rate under high pH environment while clay show contradictive results from different researchers. Further research is needed to explain more detail about the effect of pH to the sealing and healing mechanism in clay.

Meanwhile in the salinity field, clay shows a lower sealing rate and swelling strain under high salinity environment whilst concrete shows a little to no effect of salinity to the sealing and healing mechanism. This is a rather contradictive finding, thus the conclusion cannot be drawn. More data is needed to strengthen the argument.

4.4. Mechanical Aspect

In terms of mechanical aspect, both clay and concrete show a decreasing permeability value under increasing stress. The mechanism is induced by the closing discontinuity under increasing stress then decreases water flow. The interesting finding that there is a certain maximum stress level for concrete to have a sealing mechanism before permeability increases significantly due to the crack propagation. This finding is not yet discovered in clay. Thus, it will be a valuable information if the similar experiment is conducted for clay.

However, experimental results from both clay and concrete shows no information related to the effect of increasing stress to the healing mechanism. Even though there are several researchers discuss the regain mechanical properties of healed concrete, the results do not address the specific objective of how increasing stress would contribute to the healing mechanism.

4.5. Summary

The summary of all aspects above is presented under below table.

Table 5. Summary of comparison between clay and concrete

Aspects	Clay	Concrete
Hydraulic	- Experience sealing mechanism under water flow. - No inspection of sealing/healing mechanism under fully submerged condition	- Experience sealing mechanism under water flow. - No sealing/healing mechanism under fully submerged condition.
	Healing mechanism was inspected by using visual assessment	Healing mechanism was inspected by using dynamic modulus measurement
Thermal	Hydraulic conductivity is not significantly affected by increasing temperature	Faster sealing rate and higher strength recovery for healing mechanism under increasing temperature
	Swelling-shrinking capability under outdoor cyclic temperature	No specific experiment which inspected the relation of outdoor cyclic temperature to the sealing and healing mechanism in concrete
Chemical	Contradictive result for the effect of pH to the sealing rate	Faster sealing rate under high pH
	Lower sealing rate and swelling strain under high salinity environment	Salinity has a minor influence on the sealing and healing process. The

		mechanism is still dominated by the further hydration of cement.
Mechanical	- Permeability or hydraulic conductivity decreased with increasing confining stress - No inspection for effect of high stress to the sealing and healing mechanism	- Permeability or hydraulic conductivity decreased with increasing stress. - There is certain maximum stress level for concrete to have sealing mechanism before permeability increases significantly due to the crack propagation.
	No inspection related to the increasing stress and properties of healed material	No inspection related to the increasing stress and properties of healed material

5. Conclusion and Remarks

There are several conclusions of this research:

1. Both concrete and clay have the capability of self-sealing and self-healing.
2. The main mechanism in concrete is caused by further hydration of un-hydrated cement while in clay it is caused by the adsorption of water particle into the interlayer space of clay particle.
3. For hydraulic aspect, both clay and concrete experience sealing mechanism under flowing water. There is no sealing and healing mechanism under fully submerged condition in concrete while more data is needed to inspect such mechanism in clay.
4. For thermal aspect, increasing temperature has no effect to the hydraulic conductivity of clay while concrete experiences a faster sealing rate and higher strength recovery under the same condition. Relative humidity plays significant role for thermal aspect which gives indirect effect to the sealing and healing mechanism. Thus, experiments with direct exposure to the variable of temperature is needed to strengthen the conclusion.
5. For chemical aspect, concrete experiences a higher sealing rate under basic environment (high pH) while more experiment is needed for clay to obtain a better conclusion. Meanwhile, result showed that high salinity environment gave little to no effect to the sealing and healing mechanism in concrete while such environment decreased the sealing and healing capability of clay.
6. For mechanical aspect, both clay and concrete experience a decreasing hydraulic conductivity under increasing confining stress. It is needed to inspect the maximum stress on clay related to the crack propagation which might affect to the sealing and healing capability.

There are some remarks related to this study. First, the references for such topic is relatively limited, thus it might deviate the analysis and comparison process. The scarcest reference is for the chemical and mechanical aspect where incomplete and contradictory result still can be noticed in this report. More extensive laboratory tests and numerical modelling is needed to fill the gap. Second, the difference of methods between the experiments from different researchers also contributes to the deviance of the analysis thus affect to the final result. For instance, the heating process of the specimen by oven-dry method might give a slightly different result to one with the increasing ambient temperature.

6. References

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