Interaction of clay and concrete relevant to the deep disposal of high-level radioactive waste

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Abstract

A concept for the disposal of highly radioactive waste at depth in the Earth's crust using very deep bore-holes requires that the upper 2 km's of the 800 mm diameter, steeply drilled holes, be effectively sealed. This can be achieved by using dense smectitic clay where the rock is weakly fractured and strengthening with concrete when fracture zones are encountered. Earlier investigations have shown that chemical reactions between the clay and concrete can be expected both in the upper part where the temperature is lower than 90°C and in the deeper section where the temperature reaches up to 150°C. To study further this interaction, hydrothermal experiments were conducted using mixed-layer (illite/smectite) Holmehus clay and a low pH slag-based concrete placed in contact under isothermal conditions at 21°C, 100°C and 150°C for a period of 8 weeks. The sample sets, which consisted of two clay discs separated by concrete cast on the lower clay disc, were extracted in undisturbed form and exposed to uniaxial pressure for measuring the compressive strength at successively increasing pressures. Compression tests under enhanced thermal conditions led to strengthening of both the clay and concrete. X-ray diffraction and electron microscopy

analysis of the material revealed an increasing degree of cation exchange at higher temperatures with the cement, whereby Ca replaced Na in the interlayer sites of smectite layers. Dissolution of illite/smectite was also evident occurring at enhanced temperatures, with a decrease in K, Mg and Fe content with advanced alteration. The enhanced strength of clay can be partly attributed to the precipitation of cement phases from circulating fluids, including precipitation of gypsum.

Keywords: low-pH slag cement, clay, chemical analysis, mineralogical analysis, stress/strain, hydrothermal treatment,

1. Introduction

The concept of the Very Deep bore-Hole (VDH) disposal of highly radioactive waste at crustal depth is one of the recently discussed ideas that could place canisters of copper, navy bronze or titanium in long-holes (Pusch et al., 2013b; Bates et al., 2014; Beswick et al., 2014). Such disposal requires that the upper 2 km's of the steeply drilled holes, with a diameter of 800 mm, is effectively sealed with dense expandable smectitic clay. Perforated "supercontainers" would be installed sealed by clay in deeper parts of the holes where the surrounding rock has few fractures, and concrete cast where fracture zones are intersected, which typically range in length from a few hundred m's to up to hundreds of kilometers (Fig. 1).

Fig. 1. Schematic presentation of the very deep bore-hole concept. Grouting is used for reducing the inflow of water into the hole from fracture zones and for stabilizing them.

The safe closure of VDHs relies on knowledge of the chemical and physical stability of the clay and concrete materials; a theme which has been investigated in a number of laboratory and pilot studies at temperatures up to 150°C (Gaucher and Blanc, 2006; Pusch, 1982, 2013a). It is well established that concrete with ordinary Portland cement produces a very high pH caused by dissolution of $\text{Ca}(\text{OH})_2$ (portlandite) in the pore water of the cement matrix, which can alter smectite phases in the clay seals (Pusch, 1982; Huertas et al., 2009; Liu et al., 2014). In this concrete, the pH buffering is controlled by local equilibrium reactions, which work as the concrete matrix is being leached by dilute groundwaters, (van Eijk and Brouwers, 2000).

Released Ca, K and Mg in the pore water of the contacting cement can migrate into the clay and affect its physical behaviour (Pusch, 1982). The initially generated hydroxides in the porewater of clay seals in boreholes caused by casting ordinary concrete on them is generally very high (>13) and has high contents of Na, K, and Ca ions (Vigil et al., 2001; Ramírez et al., 2002, 2005; Neretnieks, 2014). This is followed by a period in which pH is dominated by equilibrium with portlandite, $\text{Ca}(\text{OH})_2$, leading to a value $\text{pH} = \sim 12.4$. This in turn is followed by a final stage with the system being in equilibrium with the CSH-type minerals formed in the cement matrix, producing a pH of ~ 10 , (Berner, 1992; Fernández, et al 2006; Bartier et al., 2013). These various stages of alkalinity can be modified by using "lower pH cement" that reduces the destabilizing impact on the smectite clay (Gaucher and Blanc, 2006). This principle was adopted in the recently described study of the mutual impact on contacting clay and concrete under conditions relevant to deep disposal (Pusch et al., 2013c). Other clay-concrete studies have shown that zeolites may form during batch tests of montmorillonite with KOH, NaOH, or $\text{Ca}(\text{OH})_2$ solutions over a period of a few months at 90°C and mixed-layer illite/smectite in K-rich solutions (Pusch, 2008; Huertas, 2000, 2009; Sanchez et al. 2006; Fernández et al., 2006). Such conditions led to concentration of Mg in the octahedral sites of the 2:1 smectite lattice or to saponite precipitation. Overall, a number of features could be identified in these experiments according to Pusch et al. (2003), namely: (1) High-alkali cement (Portland-type) degrades quicker than low-alkali cements, (2) Released elements and water migrate from the cement matrix to the clay during the early stage of initial contact, (3) The cement paste dehydrates, voids widen, and the solidified cement matrix fissures, (4) A $\text{pH} = >12.6$ is a critical value for significant alteration of the clay, (5) Ca migrates from the cement to the clay causing Na-to-Ca exchange and coagulation of the softer parts of the clay, and (6) Mixed-layer smectite/illite/muscovite clay with 25 % expandables in contact with low-pH cement does not cause significant alteration of either of the components.

1
2 Similar results were obtained from a >3 year old pilot experiment with smectite-rich clay
3 (MX80) contacting concrete, which was placed at 200 m depth under ambient temperature
4 conditions in a 5 m deep borehole with an 80 mm diameter set in granite and brackish
5 groundwater. The clay used was the well characterized smectite-rich (70-80 %) MX-80
6 bentonite (Montes et al., 2003; Perdrial & Warr, 2011), which was prepared with a dry
7 density of 1710 kg/m³ (composition given in Table 1). The concrete used was based on
8 Portland cement, silica-rich aggregate and Glenium 51 superplasticizer. The density of the
9 concrete was 2300 kg/m³. The concrete plug was cast directly on the clay plug 8 hours
10 following its placement to allow it to mature sufficiently and to prevent the low-viscous
11 concrete from penetrating downwards.

12
13 Following recovery, samples across the clay-concrete boundary were investigated for their
14 geotechnical and chemical-mineralogical properties (Pusch and Ramqvist, 2006; 2011a; Warr
15 and Grathoff, 2010; Nickel, 2012), the results of which are summarized as follows. The
16 physical properties of the concrete showed some minor change to a distance of about 20 mm
17 from the contact with clay and chemical-mineralogical alteration observed in this part. In
18 addition to the leaching of Ca and K from the cement matrix, neocrystallization of a fibrous
19 Ca-Si cement phase occurred along with the formation of some amorphous components.
20 Comparison of XRD reflections of the altered and unaltered concrete samples showed that a
21 number of reflections in the unaltered sample were smaller or absent in the altered sample,
22 attributed to cement phases that either did not crystallize in the altered concrete or have been
23 removed by dissolution. Portlandite and possibly belite were recognized and the occurrence of
24 a small amorphous reflection indicated new alteration products in the matrix of the altered
25 concrete sample (Gaucher and Blanc, 2006; Dauzeres et al., 2010).

1 The MX80 clay showed no obvious difference in hydraulic conductivity between samples at
2 distant from the clay-concrete contact and the one in contact with the concrete, despite
3 differences in density (highest 1980 kg/m³). The swelling pressure and hydraulic conductivity
4 of the latter were in fair agreement with data for clay saturated with distilled water, while for
5 the sample extending 20-30 mm from the concrete the data fit better clay saturated with 3.5 %
6 CaCl₂ solution. This indicates that the clay near the concrete contact had undergone cation
7 exchange and sorption from the percolating Na and Ca-bearing cement solutions, (de Windt et
8 al., 2004). The hydraulic conductivity of juxtaposing clay therefore increased while the
9 expandability dropped. Furthermore, the concrete was notably depleted of Ca near the clay
10 and the cement phases had undergone significant dissolution. Gypsum was also found in the
11 clay and concrete in the contact region. The clay aggregates had a characteristic irregular
12 topography probably resulting from flocculation in the presence of strong salt solutions. A
13 shift towards larger interlayer space was observed close to the concrete, reflecting the
14 occurrence of more water layers in the interlayer sites of the montmorillonite due to the
15 exchange of monovalent cations by bivalent ones (e.g. Na⁺ exchanged by Ca²⁺). The
16 occurrence of multiple XRD peaks of the air-dried smectite of varying intensities within 10
17 mm from the concrete contact indicates that the montmorillonite interlayers contained
18 heterogeneous mixtures of both bivalent and monovalent cations caused by varying degrees of
19 exchange.

20
21 Based on the reported results, it is evident that dissolution of both the smectite clay and the
22 cement matrix of contacting concrete can be significant when Portland cement is used and
23 that low-pH cement can be expected to cause significantly less damage. Since the temperature
24 conditions in the lower part of VDH's ranges up to 150°C, alteration processes can be
25 expected to be faster and probably more extensive than in most of the experiments referred to.

Therefore knowledge of the mutual impact of concrete and smectitic clay at higher temperatures is a critical requirement. This present study therefore reports on the reactions that occur between two less studied but potentially more stable types of material: A relatively stable montmorillonite-rich mixed-layer clay known as Holmehus clay and a new type of low-pH, talc-bearing, slag-based cement.

2. Materials and experimental procedure

2.1. Holmehus Clay

A Danish mixed-layer I/S clay "Holmehus clay" of Tertiary age used in this study was sedimented in nature under marine to brackish conditions. It also contains smectite, glauconite, quartz, feldspars, calcite, glass, kaolinite, Ti oxide and pyrite (Pusch et al. 2014). The smectite makes up 60% of the I/S phase. The clay is similar to the German Friedland clay that is widely used for isolating hazardous waste in landfills (Keto, 2004). The raw material was dried at 60°C, crushed and sieved to a maximum grain size of 2 mm. The chemical composition shows the Holmehus clay has less Si, Al, Mg, Ca and Na than MX80 but higher concentration of Fe and K (Table 1). The high K content of Holmehus clay can be explained by uptake and fixation of K by diagenetic processes many millions of years ago.

Table 1. Chemical (weight % oxides) and mineralogical constitution of smectite-rich MX-80 and mixed-layer Holmehus clay,

Element	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	MgO	CaO	Na ₂ O	K ₂ O	TiO ₂	SO ₃	Minerals
MX-80	63.6	19.8	5.0	3.2	3.1	2.8	1.0			Mnt+++, Qtz+, Fsp+, Cb+
Holm.	65.2	17.0	7.2	2.4	0.7	1.6	3.1	0.9	1.7	I/S+++, Mint+, Qtz+

(Qtz=Quartz, Fsp=Feldspars, Mnt=Montmorillonite, I/S=Illite-smectite mixed layer phases,
Cb=Carbonates; Minerals +++ rich, ++ intermediate, + traces)

2.2 Concrete

The cement used in this study was Merit 5000, which is a slag-based binder manufactured by SSAB Merox AB, Oxelösund. The aggregate added was crushed and ground quartzite to which quartz powder was added. Talc was added as a superplasticiser for eliminating the risk of microbial growth when using organic materials, which can also give off organic colloids that can transport radionuclides to the biosphere via groundwater. Talc has the chemical formula $3\text{MgO} \cdot 4\text{SiO}_2 \cdot \text{H}_2\text{O}$. It was manufactured by VWR Int. Co., UK. The composition of the concrete used is shown in Table 2. Similar talc-based concretes were previously tested by Pusch et al. (2013c).

Table 2. Concrete recipe.

Proportions, %			Water/cement	Aggregate/cement	Density,	pH
Merit 5000	Talc	Aggregate	ratio	ratio	kg/m ³	
Cement						
6.5	9.5	84.0	3.6	12.8	2070	10

Since the concrete should remain mechanically stable of a long-term period (Svemar, 2005; Pusch et al., 2011b), a very low cement content was used to minimize any physical change if the cement is dissolved and lost (Mohammed et al, 2013). In the event of cement loss, the very densely packed and low porosity aggregates must still provide support for the neighbouring clay seals and remain sufficiently tight and erosion resistant. Based on the natural analogues such as bottom moraine, the quartz-rich aggregate used should remain intact for very long periods of time if the talc/cement would be dissolved.

2.3. Experimental setup

Fig. 2. Upper: Sets of clay/concrete for hydrothermal treatment under isothermal conditions, the diameter of the cells was 50 mm. Lower left: compressed, water-saturated clay. Lower right: freshly cast concrete over the lower clay sample.

The sample sets consisted of two 1.5 cm thick clay discs separated by 3 cm concrete cast on the lower clay disc (Fig. 2). Ceramic filters were used for confining the materials in

hydrothermal cells with 1 mm layers of very fine quartz powder separating them from the clay samples. The layers of clay were completely water saturated by mixing the clay granules with “dry water” droplets (Bomhard , 2011) and compressing them to a dry density of 1500 kg/m³. The lower clay sample was compressed in the cell and concrete cast upon it while the upper clay sample was prepared in a separate cell and moved to reach contact with the concrete under a pressure of a few hundred kPa (Fig. 2). It had a fine hole for letting air out when fitting it in the cell two days after casting the concrete. The filters were connected to vessels with the respective solutions and the cells then placed in ovens for heating.

2.4 Hydrothermal treatment

Three cells with 50 mm diameter and 70 mm height with clay-concrete samples were each connected to vessels with distilled water and 3.5 % CaCl₂ salt solution and heated for 8 weeks at 21°C, 100°C and 150°C, respectively. The fluid pressure was held at 400 kPa for avoiding boiling.

3. Results and discussion

3.1 Compressive strength measurements

Uniaxial compression of the individual components removed from the cells was not possible without damaging them, therefore the whole sets were compressed together assuming that the weakest component fails first. The process was followed by examining photographs taken in the course of the compaction. A hydraulic loading machine was used for the purpose and controlled so that the respective pressure steps were kept constant until the compression for each step had become insignificant (less than 1 % per minute). The pressure at the start was 40 kPa, and doubled for each subsequent step until the compression reached 30 mm (about 38 % total compressive strain). The load was then increased to give complete failure.

Fig. 3 shows the successive breakdown of the sample set stored at 21°C temperature. The upper clay saturated with distilled water failed before the concrete. The compressive strength being reached when the pressure was 519 kPa, corresponding to a shear strength of about 250 kPa assuming Mohr/Coulomb behaviour. The lower saltwater-saturated clay was stronger but more brittle. The average compression modulus of the clays, being the ratio of axial stress before failure, can be estimated at 10 MPa. The concrete remained intact until the pressure had reached about 700 kPa when the total compressive strain had become about 35 %. Further compression led to complete brittle failure of all the components (Fig. 4).

Fig. 3. Compression stages at 21°C. Initial failure took place in the upper clay sample at 519 kPa pressure.

Fig. 4. Stress/strain diagram for the 21°C sample set.

Fig. 5 shows the successive breakdown of the sample set hydrothermally treated at 100°C.

The behaviour was similar to that of the 21°C set, with the clay saturated with distilled water being the first to fail. The compressive strength was reached at a pressure of around 900 kPa, corresponding to a shear strength of about 450 kPa of the clay saturated with distilled water (Fig. 6). The lower saltwater-saturated clay was slightly stronger. The average compression modulus of the clays was similar to that of the room temperature clays. The concrete remained intact until the pressure had reached about 1500 kPa when the total compressive strain had become about 40 %. Further compression led to complete brittle failure of all the components.

Fig. 5. Compression stages of the samples kept at 100°C temperature. Initial failure took place in the upper clay sample at 900 kPa pressure.

Fig. 6. Stress/strain diagram, T=100°C

Fig. 7 shows the successive breakdown of the sample set kept at 150°C temperature, where as in the other tests the weaker upper clay saturated with distilled water failed first and the stronger concrete later. The compressive strength of the clays was reached when the total strain was about 1.5 % and the pressure about 1100 kPa, corresponding to a shear strength of about 550 kPa, (Fig. 8). The compression modulus of the clays can be estimated at 25 MPa showing that they were significantly stiffer than the less heated ones. The concrete remained intact until the pressure was 3300 kPa and the total compressive strain had become about 40 %.

Fig. 7. Compression stages of the samples heated at 150°C temperature. Initial failure took place in the upper clay sample at 1300 kPa pressure.

Fig. 8. Stress/strain diagram for the 150°C sample set.

On comparing the results for the concrete with earlier investigations with no clay present in the hydrothermal cells it is evident that the compressive strength was nearly 3 times higher for the concrete without contacting clay (Mohammed et al., 2014). It had a compressive strength of 4.5 MPa of unheated concrete and 9 MPa for concrete exposed to 75°C and 150°C. This agrees with the results from the field experiments with smectite-rich clay in contact with concrete based on Portland cement (Warr and Grathoff, 2010) and hence supports the conclusion from the latter study that the chemical interaction of the two materials causes weakening.

3.2 Mineralogy and composition

3.2.1 X-ray diffraction

A set of samples were selected (3 clay and 3 concrete) from across the lower contact of the clay and concrete interface from the 21, 100 and 150°C experiments. The 6 samples were crushed using a McCrone micronizer and dried using ethanol to form a consistent powder,

1 which was measured using a Bruker D8 Advance instrument. The results of the random
2 powder diffractograms for the clay samples showing the characteristic clay mineral reflections
3 at low-angle of diffraction ($5-16^\circ$ 2θ) are shown in Fig. 9. The main dominant reflection
4 is that of illite ($10\text{ \AA}$), which is most intense in the 21°C sample and decreases at higher
5 temperatures. This decrease is considered not to reflect decreasing illite abundance, but is
6 caused by the shift of a broad overlapping illite/smectite (I/S) reflection from $\sim 11.3\text{ \AA}$ in the
7 21°C sample to $\sim 14.4\text{ \AA}$ in the 100 and 150°C treated clay. The cause of this peak shift is
8 attributed to the exchange of Na by Ca in the interlayered smectite, and the incorporation of 2
9 water-layers into the I-S structure (as opposed to 1 water-layer for Na), which is responsible
10 for the increase in the measured thickness of I-S structure. Another recognizable change is the
11 occurrence of gypsum which appears to be most abundant in the 21°C samples, and which
12 also occurs in the 100°C clay but is not detected after 150°C treatment. This trend may reflect
13 the instability and breakdown of gypsum at temperatures above 100°C , however, due to the
14 occurrence of gypsum in the 150°C concrete (see below) it is more likely to reflect the
15 heterogeneous distribution of gypsum in all samples. Minor amounts of kaolinite and chlorite
16 are present in all samples, with no major changes occurring in relation to hydrothermal
17 treatment. No cement phases could be identified in the clay samples.

Fig. 9. X-ray diffraction analysis of the Holmhus clay sample showing the clay minerals present after experiments. Red = 21°C, blue = 100°C and green = 150°C. d-values given are in Å units. The background trace has been subtracted. Lin = Linear (counts).

As the XRD patterns of the concrete showed very little difference between the samples due to the very low cement content of the concrete samples, the results are not shown here. The following features were, however, noted: 1) minor contamination of the concrete by I/S, 2) chlorite and kaolinite are evident, and 3) gypsum occurred in the 100 and 150°C samples but not in the 21°C concrete.

3.2.2 Electron microscopy

The 6 study samples were investigated by scanning electron microscopy and combined with energy dispersive X-ray (EDX) analyses of the clay and cement portions across the contact between the two materials. Analyses were undertaken using an Auriga Zeiss FIB-SEM

1 equipped with an 80mm² CCD detector. The analytical methods used have been previously
2 described (Warr and Grathoff, 2011). Secondary electron imaging revealed a variety of
3 microstructures in both the clay and cement phases at the different experimental temperatures.
4 At 21°C the clay displayed typically thin illite/smectite particles with irregular shaped edges
5 that are frequently crenulated (Fig. 10A). The contacting cement in the adjacent concrete was
6 well developed, forming thin coatings of most grains and showing a network type structure of
7 interconnecting cement grains (Fig. 10B).

8
9 The clay subjected to 100°C did not vary significantly in appearance from that of the 21°C
10 sample, with similar crenulated edges of the illite/smectite particles (Fig. 10C). A notable
11 difference is the occurrence of irregular patches of cement that coated many of the clay
12 particle and appears to have precipitated from the interaction of the fluids derived from the
13 cement and the saline CaCl₂ solution. Due to the thin nature of neocrystallized cements
14 precipitations, the composition could not be reliably determined by EDX analyses, but the
15 concentration of Ca and S in these areas indicated that gypsum was also present. The average
16 concentration of S in the clay, is however, generally less than half the concentration of that
17 measured in the cement phases (Table 4). Some S may also have resulted from oxidation of
18 the 0.3 % pyrite present in untreated Holmehus clay.

19
20 The crystalline appearance of the cement probably reflects the precipitation of calcium silicate
21 hydrate phases derived from the slag cement, which are present in too low a concentration to
22 be detected by XRD. The occurrence of such phases are probably responsible for the
23 apparent hardening of the clay beneath the concrete layer and indicates that cement-derived
24 fluids penetrated significant parts of the underlying clay layer during the hydrothermal
25 treatment. The nature of the cement in the concrete at 100°C was also well developed and it

1 coated most aggregate grains with the exception of some talc crystals (Fig. 10D). The cement
2 was, however, slightly coarser in its network texture and thicker than that developed in the
3 21°C sample, suggestive of enhanced dissolution and precipitation reactions.

4

5

Fig. 10. Secondary electron images of A) 21°C treated clay, B) 21°C treated concrete, C) 100°C treated clay, D) 100°C treated concrete, E) 150°C treated clay and F) 150°C treated concrete. I/S = illite-smectite, T = Talc, C = cement.

The clay of the 150°C showed illite/smectite particles with notably smoother edges than developed in the lower temperature samples, which can be attributed to enhanced dissolution of the clay (Fig. 10E). Localized patches of Ca-Mg bearing cement precipitates were also found within the clay, as developed in the 100°C sample. The cement phases in the concrete were similarly coarse in texture and thicker than those developed at lower temperatures (Fig. 10F), indicating similarly enhanced dissolution and precipitation reactions with penetration of cement-influenced fluids into the underlying clay layer.

The composition of the illite/smectite particles determined by EDX analyses (Table 3), shows that some changes in composition occurred with the increasing temperature of hydrothermal treatment. Mg, Fe and K show slight decreases indicating possible dissolution of illitic and or smectitic layers, whereas the Ca content increased by exchange of interlayer cations.

However, as the clay particles were commonly coated by nanometer-sized neocrystallized cement grains (including gypsum), which were increasingly evident at higher temperatures in the cement, this chemical trend also reflects the increasing degree of cement contamination (Ca-phases). The main constituents of Si and Al show no recognition changes during increasing temperature, also compared to “virgin” Holmehus clay (Table 1).

Table 3. EDX compositions (weight of oxides, n = 30) of illite/smectite and cement phases across the contact at 21°, 100°C and 150°C.

Smectite clay particles

Temperature	Na ₂ O	MgO	Al ₂ O ₃	SiO ₂	K ₂ O	CaO	TiO ₂	FeO	SO ₃	sum
21°C	1.3	2.9	19.1	62.8	3.8	0.6	1.6	7.5	0.5	100
100°C	0.8	2.6	21.1	63.3	3.4	1.7	0.9	5.8	0.5	100
150°C	2.2	2.4	19.3	59.5	3.1	6.6	0.9	5.7	0.3	100
Cement phases										
Temperature	Na ₂ O	MgO	Al ₂ O ₃	SiO ₂	K ₂ O	CaO	TiO ₂	FeO	SO ₃	sum
21°C	0.4	28.6	2.4	65.4	0.1	1.1	0	1.4	0.6	100
100°C	0.6	11.0	8.3	43.2	0.2	30.8	3.7	1.1	1.3	100
150°C	0.5	10.5	2.8	46.4	0.3	30.9	3.4	4.3	1.0	100

Attempts at measuring the cement compositions were somewhat hampered by interference of the EDX signals by the minerals underlying the cement coatings. The results presented in Table 3 should therefore be considered as rough estimates of the true composition. Despite these problems, similar trends of decreasing Mg were observed as seen in the clay minerals analyses together with a notable increase in Ca with increasing temperature. The similarities in trend between the estimated cement compositions and those observed for the illite/smectite particles, confirms that the dominant factor influencing the increasing hardness of both the cement and clay with enhanced hydrothermal treatment is the quantity and composition of the cement phases formed.

4. Conclusions

The investigation of short-term hydrothermal treatment up to 150°C on concrete made with low-pH slag-cement, quartzite aggregate and talc as a fluidizer, in contact with smectitic clay of mixed-layer montmorillonite/illite gave the following results:

- smectitic clay and low-pH concrete kept in contact for 2 months at room temperature gave insignificant changes in uniaxial compressive strength compared to earlier separately prepared and tested materials,
- the compressive strength of both clay and contacting concrete increased by 25-60 % by hydrothermal treatment at 100°C compared to the strength of samples kept at room temperature,
- the observed average increase in unconfined compressive strength of the clay is attributable largely to dehydration with a 50% higher value for the 100°C sample and a 100% higher value for the 150°C sample when compared with the material at 21°C,
- the compressive strength of clay saturated with distilled water and being in contact with concrete was lower than for samples saturated with salt Ca-rich water. The latter were also stiffer,
- the clay and concrete retained their coherence at heating to 100 and 150°C and gained significant strength. The compressive strength of the concrete was, however, nearly 2-3 times higher for the concrete without contacting clay.
- the mineralogical and chemical changes caused by the hydrothermal treatment were similar for both 100°C and 150°C. There are indications of enhanced dissolution of the illite/smectite phased during hydrothermal treatment and Ca exchange of Na occurs in interlayer sites. More extensive invasion of the clay by cement fluids and precipitation of cement phases can explain much of the strengthening and increase in stiffness of the clay,

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