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The effects of the thaumasite form of sulfate attack on skin friction at the concrete/clay interface

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ABSTRACT

The paper presents the effects of thaumasite sulfate attack (TSA) on skin friction at the concrete/clay interface. Using clay-restrained conditions thaumasite formed attached to the concrete culminating in thaumasite layers of up to 24 mm depending on interface pH and applied pressure. Thaumasite at the interface did not decrease the shear strength including skin friction and cohesion. Therefore it was concluded that TSA occurring at piles or foundation bases does not affect the stability of the superstructure regarding loss of friction and settlements.

1. Introduction

Engineers have, for many years, designed to protect against the conventional form of sulfate attack, which occurs when sulfate in ground water reacts with calcium aluminate hydrates (CAH) in the concrete. Owing to its discovery in the foundations of a number of bridges a second form of sulfate attack – the thaumasite form of sulfate attack (TSA) – has received considerable attention in recent years. In the case of TSA the calcium silicate hydrates (CSH), the main binding agent in all Portland cements, are targeted. Whereas the consumption of CAH during conventional sulfate attack causes expansion and, ultimately, cracking of the cement matrix [1], TSA leads to a transformation of the cement matrix into an uncohesive mass from the surface inwards. Much of the research effort to date has concentrated very much of the formation mechanisms on TSA and the identification of concrete mixes capable of resisting it.

Structural effects of the thaumasite form of sulfate attack due to loss of strength, stiffness and resistance to ionic diffusion of the gradual progressive deterioration zone were described in the report of the Thaumasite Expert Group (TEG) [1]. The main effects are as follows:

(i) loss of concrete cross-sectional area;
(ii) loss of cover concrete to the reinforcing bars and, possibly, beyond the bars;
(iii) loss of bond between reinforcement and concrete in affected zones;
(iv) loss of pile skin friction;
(v) loss of foundation base friction;
(vi) settlement, inducing structural damage;
(vii) loss of durability as a result of a loss of reinforcement protection.

The TEG classifies effects (i) to (iii) as purely structural, (iv) to (vi) as soil-structure system and effect (vii) as a durability issue which may have structural implications.

The effects listed above are able to have a negative impact on the structural integrity; however, public safety will be rarely endangered due to the gradual nature of TSA. Signs of deterioration of a substructure will be visible in the superstructure above through e.g. progressive cracking before significant loss of stability occurs.

Changes in soil-structure interactions caused by softening of the concrete surface due to TSA can be defined [1] on the one hand as the loss of friction at the affected areas, i.e. reduction of sliding resistance to lateral loads, as for instance in foundations, and reduction of load capacity of piles, characterised by skin friction. On the other hand pure structural effects due to loss of effective cross-section may reduce the capacity and increase the effective slenderness of an element. TSA may reduce the cross-sectional area of a concrete element with a water–cement ratio (w/c) = 0.55, and cement content (c) = 320 kg/m^3 (Portland cement) with an annual rate of deterioration of up to 1.8 mm per exposed face [2]. The TEG [1] reported a case of cast-in-place concrete piles in Lower Lias Clay where a pile had been affected over up to 50% of the exposed area. The general depth of deterioration was found to be less than 20 mm but at one location the softening of the cement paste had progressed up to 70 mm.

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The bond strength between reinforcement and concrete may also be affected depending on the extent of the softened zone [3].

Actual cases of loss of structural integrity in the field have not been found apart from a structure in the Canadian Arctic, where the columns supporting a building had to be replaced after two years in an aggressive environment [4,5]. The affected pile described by the TEG did not show negative structural effects either. This may be partly due to the large safety factor which is used during the design of piles. This factor is generally two or greater and includes allowances for uncertain ground conditions as well as for construction uncertainties and long term durability below ground. The probability of the worst case scenario actually occurring is very low. However, there is a lack of knowledge about the effects of TSA on skin friction which may be either negative or positive.

2. Methodology

2.1. General

To investigate the effects of TSA on skin friction at the soil/concrete interface of foundations and piles a number of variables were studied: concrete mix, clay type, casting surface – top cast to simulate precast concrete or bottom cast to simulate cast in-situ concrete, and confining pressure applied during thaumasite formation. The following key criteria had to be met to determine the effect of TSA on skin friction:

- thaumasite must form in a reasonable amount of time,
- thaumasite must not become detached from the specimen,
- to simulate underground conditions thaumasite must form under some confining pressure and,
- the specimen must be transferred to the shear strength measurement equipment, a large shear box, without disturbing the clay/thaumasite/concrete interfaces.

The shear strength at the concrete/thaumasite/clay interface was determined according to BS 1377-7:1990 by the direct shear test with consolidated drained conditions using a direct shear box apparatus. The equipment was modified so that failure would be allowed to occur on the weaker of the following planes:

(i) at the concrete/thaumasite interface,
(ii) within the thaumasite,
(iii) at the soil/thaumasite interface, or
(iv) within the clay.

This is in contrast to a typical shear box test where the failure plane is determined by the interface between upper and lower parts of the shear box.

The effect of TSA on the shear strength parameters at the interface was evaluated using two methods:

Method 1 evaluated changes in the shear strength using the two separate parameters of angle of skin friction δ' and cohesion c'_a. The angle of skin friction δ' describes the shearing resistance at the concrete/clay interface and is related to the coefficient of friction μ between the concrete and the adjacent clay as follows: $\mu = \tan\delta'$. The cohesion c'_a describes the ability of the clay to adhere to the concrete at the interface so that an initial significant shear force is required to destroy this adherence bond. A reduction in either of these two parameters would lead to a reduction of interface shear strength [6]. Changes of the shear strength parameters, depending on the average amount of thaumasite formed at the interface of one set of specimens, were analysed using the ratio of the shear strength parameters affected by TSA to the parameters obtained from the control specimens, these being $\delta'_{TSA}/\delta'_{control}$ and $c'_{a,TSA}/c'_{a,control}$.

Method 2 evaluated the effect of TSA on the interface shear strength according to the peak and residual shear strength τ. The factor of change, 'TSA-factor' was determined at each single interface for the shear strength, $\tau_{TSA}/\tau_{control}$.

2.2. Type of specimen

For the skin friction investigation a special type of specimen, a square box that fits into the large shear box apparatus, was

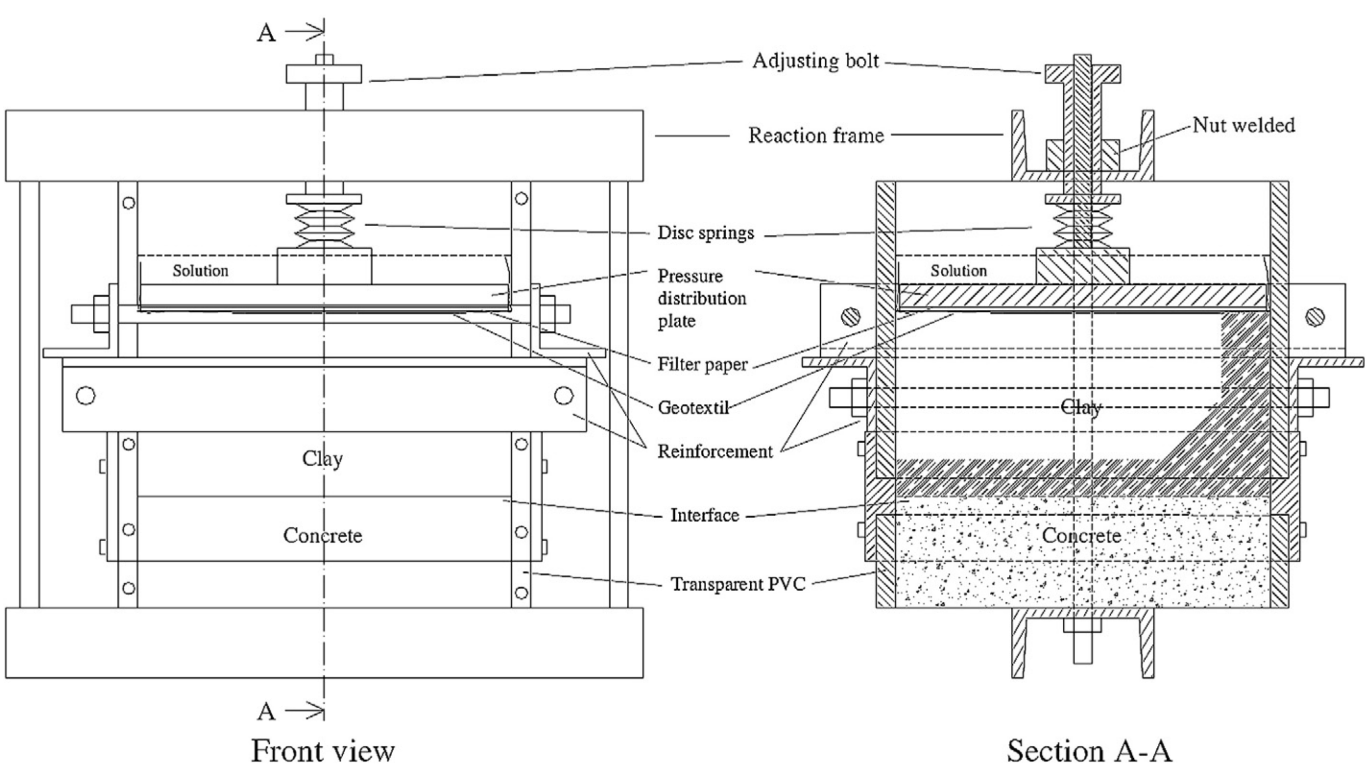

Fig. 1. Schematic representation of shear test specimen with pressure frame.

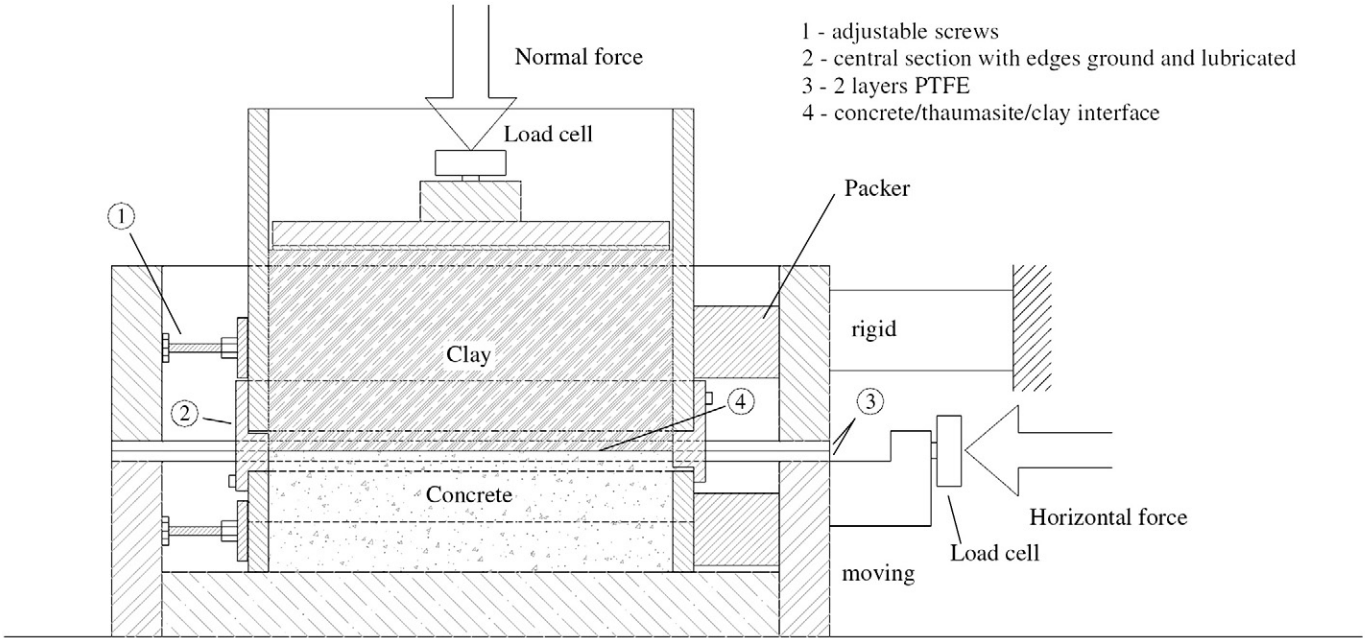

Fig. 2. Schematic representation of specimen installed in shear box apparatus.

developed, see Fig. 1. The box was divided into 3 parts, a lower box filled with concrete (h = 50 mm), an upper box containing clay and aggressive solution (h = 160 mm) and a removable middle part (h = 20 mm) at the interface between concrete and clay. The removable section was provided so that it was not necessary to demould the whole specimen before the test. This avoided unnecessary disturbance which would influence the result of the shear strength test. The central section was unfastened after the box was fixed in the test equipment. This exposed section allowed failure to occur on the weakest plane in the system concrete/thaumasite/clay. Fig. 2 represents the arrangement of how the shear test specimen was installed in the large shear box apparatus. The upper section of the box, where a normal load is applied onto the specimen, is rigid and the lower section is able to move.

To simulate the effect of lateral earth pressure in a foundation it was necessary to develop a method of applying a constant pressure throughout the thaumasite formation period. Assuming a unit weight of soil (γ) = 20 kN/m³ three different depths were simulated: 0.5 m (10 kPa), 2.0 m (40 kPa) and 3.5 m (70 kPa). The maximum applied pressure was governed by the strength of the test equipment. Pressure was applied to the top surface of the clay using an arrangement of between six and twelve disc springs arranged in series and a reaction frame. The required pressure was applied by compressing the springs to a required displacement, which could then be adjusted to 0.1 mm using a hollow nut and bolt arrangement. The disc springs were calibrated by the manufacturer and used in their optimum long term loading range to reduce creep effects and obtain a constant performance over the duration of the experiments. The resolution of 0.1 mm enabled the spring load, and, hence, the applied pressure, to be maintained, in the worst case, to an accuracy of +/−7.6%. The displacement was measured monthly at three reference points, between a bearing plate on the pressure distribution plate and the adjusting bolt, using a digital vernier caliper. Disc springs are sensitive to small relaxations; however, the absolute value of the load applied was not considered to be critically important to simulate the three different depths. The monthly adjustment was considered to be sufficient. The pressure frame is illustrated in Fig. 1. The shear tests were performed 18 months after the load was applied through the pressure frame and in total 27 months after the storage period in the environmental chamber (see Section 2.3) started.

2.3. Variable combinations

The effects of TSA were studied with several variable combinations as detailed in Table 1. Three different concrete mixes were used and two of these [Mix 1 (c = 290 kg/m^3, w/c = 0.75); Mix 2 (c = 320 kg/m^3, w/c = 0.55)] correspond to mixes used by the Building Research Establishment (BRE) in the Shipston-on-Stour field trial [7,8]. Mix 3 consists of 320 kg/m^3 cement with w/c = 0.75. The cement type used was a Portland Cement CEM I 42.5 N with a C_3A content of 8%. The carbonate-containing aggregate was a Jurassic Oolitic limestone in two fraction 0–4 mm and 4–20 mm with the grading shown in Table 2.

To simulate underground conditions three different pressures were applied to the interface. Two casting faces – topcast and bottom cast face – were used to differentiate between precast and cast in-situ concrete elements. The top cast surface represents precast conditions whereas the bottom cast face represents cast in-situ conditions where concrete was cast directly against the clay. The sulfate-containing Lower Lias Clay (LLC), with a sulfate content of 2.03–2.45 g SO_4/l according to BS 1377-3, and the non-sulfate containing English

Table 1
Variables investigated.

Concrete mix	Applied pressure (kN/m^2)			Method of casting		Clay type		Storage solution	
	10	40	70	Pre-cast	In-situ	Lower Lias	ECC	Sulfate solution	Water
1 (290–0.75)	x	x	x	x	x	x	x	x	x
2 (320–0.55)	x	x	x	x	x	x	x	x	
3 (320–0.75)	x	x	x		x	x	x	x	

Table 2
Size analysis of limestone aggregate, BS 812-103:1985.

Sieve size [mm]	Fraction 0–4 mm %-Passing	Fraction 4–20 mm %-Passing
20		100
14		79
10		49
5	100	3
2.36	78	1
1.18	56	
0.6	39	
0.3	15	
0.15	4	
0.075	2	
0	0	

China Clay (ECC) were used as soils. The two soils consist of kaolinitic clay and their particle distributions can be found in Table 3. The pH of the two LLC and ECC was determined to be 7.7 and 5.4, respectively, in accordance with BS 1377-3. The specimens were filled up with a reactive 1.8% sulfate solution ($MgSO_4{}^*7H_2O$) to enhance the thaumasite formation and stored in an environmental chamber at a constant temperature of 6 °C up to 27 months. Control specimens, consisting of concrete/clay composite specimens, of Mix 1 concrete were produced and stored in distilled water under the same conditions for 6 months.

3. Results

3.1. Interface deterioration

The concrete/clay interface deterioration under restrained conditions was determined after the shear tests were performed. The thaumasite layer measured comprised the depth of deteriorated, i.e. softened, concrete and the expansion relative to the original surface caused by the formation of the more voluminous reaction products. The depth of the thaumasite layer was determined by pushing a needle into the concrete until solid concrete was reached which, however, may have been affected by TSA in a microscopical but not in a macroscopical scale. The travel distance of the needle was measured using a digital vernier calliper. The depth of deterioration stated in Table 4 is the mean value of a series of eight to ten readings at each of the two specimens with the same pressure and the accuracy was limited to one quarter of a millimetre. In [9] it is shown that 50% of the measured thickness of the thaumasite layer corresponded to the depth of deteriorated concrete and 50% is associated with expansion. The worst thaumasite layer measured was 24 mm as shown in Table 4. The thickness of the thaumasite layer depends on the interface pressure and the interface pH. The lower interface pH enhanced the thaumasite formation. The pH at the boundary with LLC (pH 11.1) was higher but less thaumasite was observed than at the boundary with the ECC (pH 9.3–10.5). The interface pH was determined at the adjacent 10 mm of clay in accordance with BS 1377-3. Crammond [10] reported that the majority of TSA affected concretes in the UK have been completely buried up to 5 m below ground. However, enhanced thaumasite formation was still observed at the simulated depth of 3.5 m, and, therefore, it is suggested that thaumasite is able to form above a depth of 5 m.

Table 3
Soil particle size distribution.

Particle size distribution	LLC [%]	ECC [%]
>2.0 mm	4	0
2.0–0.06 mm	10	0
0.06–0.002	41	50%
<0.002	45	–
0.002–0.001	–	12
<0.001	–	37

Table 4
Thaumasite layer depending on clay, casting surface, pressure and mix at age of 27 months.

Mix		Precast surface with pressure of 10 kPa	40 kPa	70 kPa	Cast in-situ surface with pressure of 10 kPa	40 kPa	70 kPa
Thickness of thaumasite layer at boundary [mm] measured to an accuracy of +/−0.25 mm							
Lower Lias Clay (interface pH 11.1)							
Mix 1	290 0.75	6	2.75	2.75	3.5	2	1
Mix 2	320 0.55	12.5	6	4.5	7	1.5	2.5
Mix 3	320 0.75				3	3.5	5
English China Clay (interface pH 9.3–10.5)							
Mix 1	290 0.75	24	14	11.5	10.5	7	4
Mix 2	320 0.55	16	8.5	9.5	3	0	0
Mix 3	320 0.75				10	5	2

The deterioration observed at the precast surface of the clay-restrained specimens was more severe than in investigations using unrestrained specimens [2]. There it was shown that TSA deterioration rates of up to 1.8 mm/year are possible for a commonly used concrete conforming to Mix 2. The estimated actual depth of concrete deterioration of Mix 2 under 10 kPa clay-restrained conditions is 6 mm and 8 mm for Lower Lias Clay and English China Clay, respectively after 27 months. This is based on the assumption that the actual depth of deterioration is 50% of the total thickness of the thaumasite layer.

The thaumasite layer showed different appearances (Fig. 3). The reddish and greyish layers were investigated in respect to their compositions using X-ray diffraction. Representative samples of deteriorated material were collected from the surface, dried at room temperature, ground to less than 50 μm, homogenized and then about 1 g of material was analysed with regard to its mineralogical composition. The Siemens D5000 powder X-ray diffractometer was used with a silicon powder standard. The analysis of the mineral concentrations of the two layers was carried out using the software program 'DIFFRAC^{plus} EVA'. This method acknowledges the difficulty in obtaining reliable absolute quantitative values of minerals, and is a semi-quantitative method which is used to compare concentrations without stating absolute values. This approach showed that the older reddish reaction layer zone was enriched with gypsum whereas

Fig. 3. Different appearances of TSA layer.

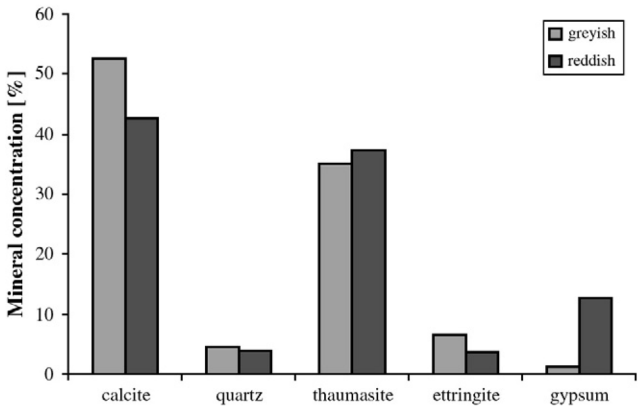

Fig. 4. Mineral concentrations of TSA layers.

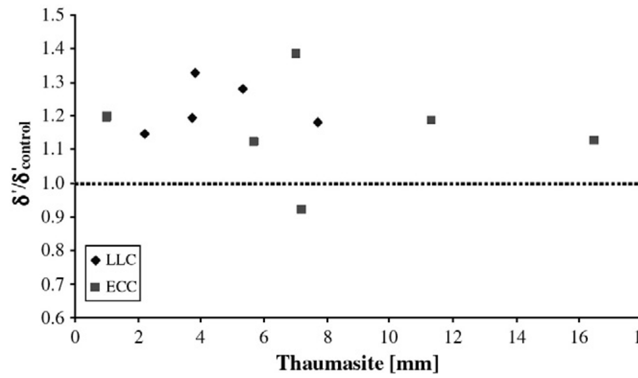

Fig. 5. Thaumasite influenced changes of skin friction δ′ for all specimen sets, age 27 months.

the newly formed greyish reaction products contained less gypsum (Fig. 4).

3.2. Comparison to field results

The extent of TSA attack at clay restrained specimens has been evaluated using the 'wear rating' method introduced by BRE [11] and compared to the results of the parallel laboratory trial to the Shipston-on-Stour field trial [12], see Table 5. Crammond [12] stated that the field observations correlated well with the laboratory results obtained after three years.

The level of attack measured on Mix 2 (w/c = 0.55; c = 320 kg/m^3) specimens (Table 4) was converted into wear ratings to be comparable with the conforming BRE concrete (w/c = 0.58; c = 320 kg/m^3). However, the BRE wear ratings were determined by measuring the diagonals of cubic specimens before and after deterioration. Cubes have an increased vulnerability to TSA at their corners, and, hence, wear ratings from the BRE cubes would be expected to be greater than those from the Authors' specimens for which the enhanced deterioration of the corners was neglected and equal deterioration on each side of a 100 mm cube was assumed so that an idealised square deteriorated cube was obtained. In addition the laboratory specimens used by BRE were not subjected to any pressure and were not in contact with clay. Hence, the wear rating values of the lowest restraint in the Authors' investigation are used for comparison and were interpolated to 12 months assuming linear deterioration. Table 5 represents wear ratings after 12 months exposure in the laboratory.

The wear ratings for the precast face are up to 5 and are similar to the ratings from BRE; however, the increased vulnerability of the corners was not included. Therefore it is assumed that the actual wear ratings are slightly higher, despite there being a good correlation between the deterioration at the shear strength specimens and the cubes tested at BRE. Additionally the deterioration measured at unrestrained specimens in a parallel laboratory investigation [9] was converted into a wear rating which is 1.3 for Mix 2. This does not correlate well to the results obtained by BRE and the clay restrained specimens. The difference between both the Author's and BRE's unrestrained specimens may be an effect of the more susceptible corners taken into account by BRE. However, clay-restrained specimens are more susceptible to TSA than unrestrained concrete specimens stored in an aggressive solution.

Table 5
Wear ratings [mm].

Authors				BRE [12]	
	LLC	ECC	Unrestrained [9]	PC (10% C_3A)	PC (7% C_3A)
Precast	3.9	5.0	1.3	3.5; 4.0	4.5; 5.0
Cast in-situ	2.2	0.9	-		

3.3. Physical interactions – skin friction

The effect of TSA on the shear strength parameters at the interface was evaluated using two methods. The angle of skin friction ratio $\delta'_{TSA}/\delta'_{control}$ obtained from Method 1 was generally scattered above 1.0 with one exception where $\delta'_{TSA}/\delta'_{control} = 0.92$, as can be seen in Fig. 5. A clear trend line for thaumasite influenced changes on skin friction in the LLC and ECC interfaces was not possible to obtain. However, a generally increased skin friction was observed when thaumasite occurred. The influence of the thaumasite formation on the shear strength parameters was greater for the cohesion c'_a, see Fig. 6. A significant positive effect of TSA was observed at the ECC interface which showed an increase of cohesion of around 40% per millimetre of thaumasite. The cohesion at the Lower Lias Clay interface increased with each millimetre of thaumasite up to 14% but one outlying result was found with 0.86.

The trend obtained from Method 2 for the English China Clay showed increases of shear strength of up to 8% (as shown in Fig. 7) and 5% per millimetre of thaumasite formed for the peak shear strength and the residual shear strength, respectively. The trend of the shear strength development at the interface with LLC was considered as positive although the correlation coefficient was very weak, see Fig. 8. The effect of TSA on shear strength is summarised for both methods in Table 6.

The two methods showed an increase of shear strength for TSA affected specimens; however, the shear plane mainly occurred within the clay in specimens with the artificial very fine grained ECC adjacent to the concrete. At the interface with the naturally coarse grained

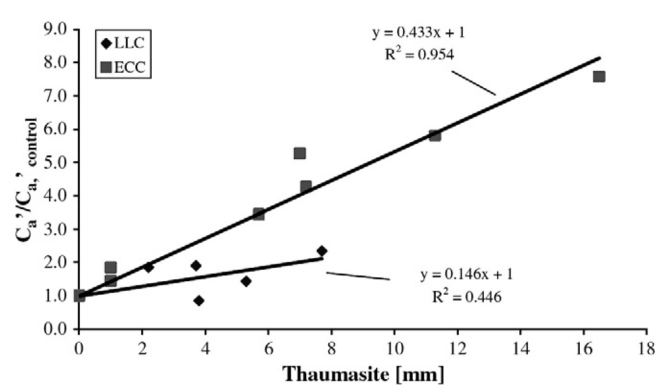

Fig. 6. Thaumasite influenced changes of cohesion c_a' for all specimen sets, age 27 months.

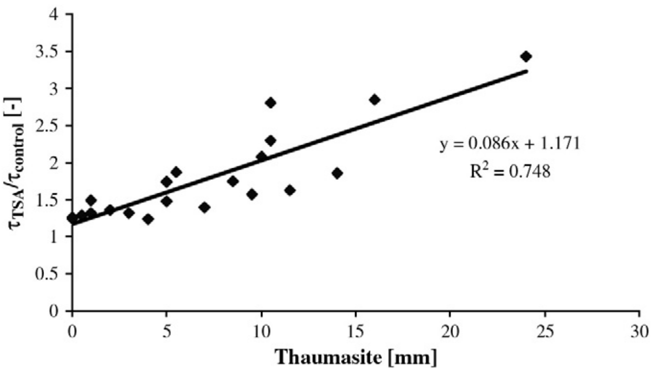

Fig. 7. Relationship TSA-factor/thaumasite for ECC samples, peak strength, 27 months.

LLC, the shear plane was predominantly observed at the interface of the thaumasite/clay and within one millimetre of the clay from the interface. Shearing at the control samples occurred directly at the interface which was rarely observed at the TSA affected interfaces.

The positive effect of TSA on skin friction at the concrete/clay interface is mainly due to the confining effect, caused by the expansion of the thaumasite layer. This causes a local increase in pressure and therefore compaction of the clay adjacent to the concrete. A secondary beneficial process affecting the skin friction and cohesion is suggested to be long term chemical interactions between concrete and clay at the interface [13,14]. The increase of pH due to the presence of hydroxyl ions results in solidification/cementation processes in the clay which increases strength [15]. This solidification was visually observed and confirmed by obtaining the pH gradient towards the interface. The pH of the LLC rose from 7.7 to 11.1 and of the ECC from 5.4 to 9.3–10.5. This secondary beneficial effect is independent of the presence of TSA and occurs at all concrete-clay interfaces but is not considered in standards.

4. Discussion

It was anticipated that the effect of thaumasite would be to decrease the shear strength and its parameters, angle of skin friction and cohesion, at the soil/structure interface. This assumption was not confirmed and reverse effects were observed. Furthermore the soft thaumasite did not serve as the weak point during shearing; which was observed to be either at the thaumasite/clay interface or within the clay.

It is suggested that the current practical guidance with its assumptions for surface roughness and the current safety factors offer a potential degree of safety combined with guidelines dealing with TSA. However, if TSA occurs and forms a soft surface then changes of the surface roughness are expected. The roughness might decrease where cement paste transforms into thaumasite but, on the other

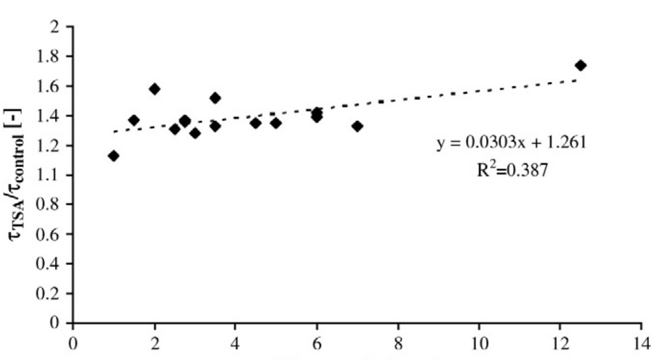

Fig. 8. Relationship TSA-factor/thaumasite for LLC samples, peak strength, 27 months.

Table 6
Summary of percentage effect of TSA on shear strength.

Interface	Method 1		Method 2	
	δ'	c'_a	τ	$\tau_{residual}$
LLC	10%	14%/$mm_{th.}$	Positive.	Positive
ECC	10%	40%/$mm_{th.}$	8%/$mm_{th.}$	5%/$mm_{th.}$

hand, increases due to mechanical interlocking with solid embedded aggregate grains. The findings of this investigation lead to the conclusion that the roughness is not affected negatively, and the skin friction coefficients, depending on casting face in accordance with BS EN 1997-1:2004, are sufficient.

However, further investigation of the concrete surface roughness in an in-situ concrete/thaumasite/clay system might be of interest. Furthermore the expansion process may distribute in the bulk of the soil and the positive effect observed on skin friction and cohesion may disappear. If the confining effect, caused by the expansion of the thaumasite layer, is lost then the results of this investigation may not be applicable to the field. It is necessary to validate the findings of this investigation with measurements of the confining effect at TSA affected piles in the field.

5. Conclusions

In general it was concluded that the formation of thaumasite at the clay/concrete interface does not negatively affect the skin friction, and that the stability of TSA affected concrete piles and foundations is not compromised as a result of a loss of friction.

Particular conclusions are:

- Deteriorated interface layers of up to 24 mm of TSA reaction products formed in 27 months. The thickness depended mainly on the interface pH and interface pressure.
  - Enhanced TSA occurred at a relative lower pH (9.3–10.5) compared to pH 11.1.
  - The thickness of the TSA products decreased with an increase of confining pressure at the interface.
- Increased gypsum formation during the end stages of TSA caused by the disintegration of ettringite.
- The effect of TSA on the angle of skin friction δ' was generally positive and an increase in skin friction of up to 10% was measured when thaumasite occurred. The cohesion increased significantly due to the formation of thaumasite. Nonetheless, this significant positive effect should not be taken into account in the assessment of TSA affected foundation structures.
- Both peak and residual shear strength increased with increasing thaumasite.
- The positive effects of TSA on skin friction are due to the confining effect which is caused by the restrained expansion of the deterioration products.
- The TSA affected interface zone is not the weakest zone within the concrete/thaumasite/clay interface. The shear plane mainly occurred in the clay and in the clay close to the interface or within a combination of thaumasite/interface/clay with greater than 60% of surface area in the interface.
- Substructures built under guidance not considering TSA are considered to be stable according to this investigation and new structures are sufficiently protected for the occurrence of TSA due to concrete specifications. However, TSA cannot be precluded and positive side effects may disappear.
- The current practical guidance with its assumptions for surface roughness and the current safety factors offer a potential degree of safety combined with guidelines dealing with TSA.

Acknowledgements

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