Engineering properties of chalk with regards to cliff slope stability

Mechanical properties of chalk and the impact of weathering on the UCS and tensile strength

Beachy Head chalk cliff, U.K.

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Abstract

Coastal chalk cliff instability is a major issue in the UK's southern region. In order to further the understanding into what drives and influences chalk cliff collapse, a series of laboratory tests have been done on samples taken from West Melbury Marly Chalk, Seaford Chalk, Newhaven Chalk and Lewes Nodular Chalk. Tests have been done to find out if there is anisotropy in permeability, what the influence of weathering is on the tensile strength and what the influence of sea water cycles on the UCS strength is. No anisotropy permeability has been found. Significant weakening has been found due to progressive mass-loss from dissolution in vinegar. No weakening from salt water cycles has been found. Between the grey chalk and white chalk subgroups, big differences exist in the behaviour when exposed to weathering.

Preface

First of all, I would like to thank Dr. James Lawrence for supervising and giving me the opportunity to be part of the research. I would also like to thank Gosia Mider, Yunchuan Li Junzhe Lui for the instructions and teamwork in the laboratory.

Acknowledgements and project background

Dr. James Lawrence, senior lecturer at Imperial College London, is doing research focused on upper cretaceous chalk. He is focusing on the engineering properties of chalks in coastal environments.

Supervised by Dr. James Lawrence, three MSc-students are conducting laboratory tests on chalk samples from different formations found in the UK’s East-Sussex region. Gosia Mider (MSc) is doing triaxial permeability tests to see if there is anisotropy in the permeability. Yunchuan Li (MSc) is doing Brazilian Tensile strength tests on samples of various degrees of weathering to determine the impact of weathering on the tensile strength. Junzhe Liu (MSc) is doing UCS strength tests to determine if there’s weakening from the formation of salt crystals within the pores. I’ve joined their research for eight weeks through the International Research Opportunity Program at Imperial College London, during which I have been shadowing the MSc-students and taking over some of the laboratory testing. I have also individually analysed the test results of all the tests done. Data is taken from Gosia Mider, Yunchuan Li and Junzhe Liu. Only raw data from weight/dimension measurements and laboratory testing has been shared. All data has been processed individually.

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1. Introduction

1.1 Problem statement

Cliff collapses like the one shown in figure 1 have been a big issue in coastal regions in multiple countries. The chalk cliffs of the UK's East-Sussex and Kent region and of France's Normandy region are examples of chalk cliffs that regularly collapse. These collapses are hazardous because large portions of chalk cliff fail, endangering people living nearby or visiting the cliffs. Understanding what drives the collapse of these chalk cliffs is essential in protecting the coastal region, as well as for guaranteeing safety for those living in or visiting the region. Research has been done before on the white chalk subgroups, but relatively little is known about the grey chalk subgroup. This research is done as part of a bigger investigation to further our understanding of the geo-mechanical properties of the chalk, with the end goal being to understand and prevent cliff collapse at chalk-rich coastal regions.

Figure 1: example of coastal chalk cliff collapse (picture by BBC)

1.2 Research objectives

The goal of this research is to develop a better understanding of the mechanical properties of the white and grey chalk subgroups. Understanding the effects of weathering-processes on the strength of the chalk will lead to furthering the understanding of what drives coastal cliff collapse. Three tests will be done, which will be discussed in section 5. By doing these tests we will get a better understanding of how these processes affect the strength of the rock mass. When we analysed the results of these tests, we can also to relate them to each other by seeing if there are any correlations between the tensile and compressional strength of the unweathered samples.

1.2.1 Anisotropy in permeability

The chalk has been subject to different horizontal and vertical stresses during its consolidation in geological time. This most likely leads to anisotropic permeability. Flow of water is an important cause of chemical weathering within a rock mass, especially in the case of rocks consisting mainly of calcium carbonate. If a small crack is present, a pathway for water to flow through will be created, increasing the rate of chemical weathering due to solution along the contact surface. Understanding how water flows through the rock mass will help us understand the weathering process better. To do this, we will take samples in horizontal and vertical direction and see if there's anisotropy in the permeability. This will be done by triaxial permeability testing.

1.2.2 Tensile and compressional strength

Coastal regions with chalk cliffs face chemical weathering from sea- and rainwater which lowers the strength of the rock mass. Some of the types of weathering of chalk in a coastal environment will be simulated with the goal of seeing how it influences strength of the chalk. We will do Brazilian Testing of unweathered samples and of samples of different percentage of mass loss due to submerging in vinegar. We will also saturate some samples with salt water, let it dry out so the salt would crystalize, and then saturate it again.

1.3 Research questions

The main research questions are:

- Is there anisotropy in the permeability of the chalk samples?
- How does chemical weathering by dissolution affect the tensile strength of the chalk?
- How does evaporation of salt water from the sample, and the associated forming of salt crystals, affect the uniaxial compressive strength of the chalk?
- Is there a relation between the unweathered chalk's tensile- and compressive strength? And if so, can this be extrapolated to the weathered samples?
- How can we apply these results to further the understanding of coastal chalk cliff collapse?

2. Literature review

2.1 Geology and lithology

All tested samples are taken from upper Cretaceous chalk formations. The Chalk stratigraphy in the UK in revised by the British Geological Survey (BGS) and uses a classification based on rock mass properties. This is a different classification than the ICS geological timescale. The lithostratigraphy can be found in Appendix A. The locations of the sites where samples have been collected are shown in figures 2 and 3. Southerham Grey Pit provided samples of West Melbury Marly Chalk (grey chalk). Seaford Chalk (white chalk) was collected at Birling Gap. Lewes Nodular Chalk was collected at Hope Gap, and Newhaven chalk was collected at Telscombe.

Figure 2: map of the greater area of sites for sampling

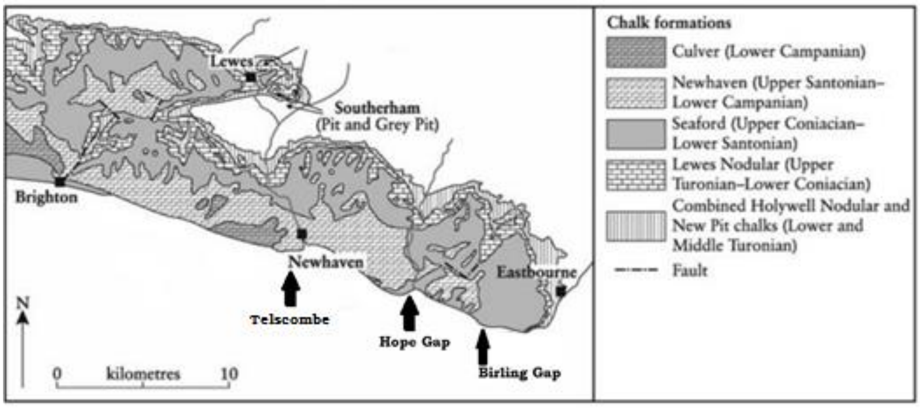


Figure 3: Geological map of the area from which samples are taken. Edited after Mortimore, R.N., 2001

Lithological descriptions:

West Melbury Marly Chalk (grey chalk): "Buff, grey and off-white, soft, marly chalk and hard grey limestone arranged in couplets. In general between 15-25m thick." (BGS). "Rhythmically bedded layers of thick marls and thinner sponge-bearing marly limestones" (Mortimore, R.N., 2001).

Seaford Chalk (white chalk): "Firm white chalk with conspicuous semi-continuous nodular and tabular flint seams. Hardgrounds and thin marls are known from the lowest beds. Some flint nodules are large to very large. Thickness in the range of 50-80m." (BGS).

Newhaven Chalk*:* "Composed of soft to medium hard, smooth white chalks with numerous marl seams and flint bands, including abundant Zoophycos flints. The formation is known to contain distinct phosphatic chalks of limited lateral extent." (BGS).
Lewes Nodular Chalk*:* "Composed of hard to very hard nodular chalks and hardgrounds (which resist scratching by finger-nail) with interbedded soft to medium hard chalks (some grainy) and marls. The softer chalks become more abundant towards the top. Nodular chalks are typically lumpy and iron-stained. First regular seams of nodular flint, some large, commence near the base and continue throughout." (BGS).

2.2 Impact of weathering and anisotropy in permeability

Research has been done on sea saltwater weakening of chalk and the impact on the slope stability, for the white chalk subgroup, showing that coastal chalks are up to 55% weaker than their inland equivalents (J.A. Lawrence et al, 2013). Wetting cycles with salt water have a significant impact on the UCS strength of white chalk samples; it weakens the samples considerably. We will do similar tests on grey chalk to see if it has the same effect. Anisotropy in permeability has not been tested for before so there is no data available because in previous researches the orientation of the samples has not been recorded. Similar weathering tests have been done by Dr. M. Ciantia on calcarenite, which show that accelerated weathering decreases the tensile strength of calcarenite samples. (M. Ciantia. 2013).

2.3 Cliff failure mechanisms

For a better understanding of the bigger picture in which this research should be placed, I will discuss some of the failure types. Wave driven undercutting of the cliff affecting the stresses within the rock-mass and eventually leading to vertical collapse of a part of the cliff, is the most well-known cause of cliff collapse, but not the only one. Vertical failure can be caused by pre-existing fracture sets, or along newly created decompression fractures, parallel to the cliff (Duperret et al, 2004). Sliding failure type has been observed in cliffs made of two chalk units, where the scar has a vertical upper part and an inclined lower part, with an overall mechanism of sliding characterized by an outward tearing process (Duperret et al, 2004). Wedge and plane failure type occurs when two or three fracture sets cross. This only occurs in chalk units that are characterized by conjugate sets of stratabound fractures, which cross each other on the cliff face. (Duperret et al, 2004). Other complex failure types occur when three or more different types of chalk interact in a complex way. About one third of the total amount of observed failures is not classified in these three types.

3. Methodology

3.1 Triaxial Permeability Test

3.1.1 First set of triaxial permeability tests

To prepare the samples, chunks of rock have been taken from the field of which orientation has been recorded. These have been sawn in smaller pieces and then processed into cylindrical samples of 76mm x 38mm (height x diameter), with horizontal and vertical orientation. See table 1 for a list of samples tested. A full list of samples prepared can be found in Appendix B.

For the permeability test a triaxial testing device has been used according to the British Standard (British Standard, 1990) for permeability testing in triaxial apparatus. Data has been collected every 3 seconds. Ram Pressure has been kept at a constant 90 kPa. An effective pressure of 50 kPa has been maintained over the sample. Cell Pressure and Back Pressure have been set to 200 kPa and 150 kPa respectively, and increased every 30 minutes according to Table 2 until the

Sample	Formation	height (mm)	diameter (mm)	weight (g)	Density (saturated) (g/cm3)	tested in first round	tested in second round
BG-2v	White Chalk	76,25	38,357	176,963	2,008461345	**yes**	no
SGP-1v	Grey chalk	76,6	38,19	205,597	2,343143062	no	**yes**
SGP-1h	Grey chalk	76,733	38,343	207,378	2,340552803	no	**yes**
SGP-2h	Grey chalk	76,847	38,377	207,782	2,337486324	**yes**	**yes**
SGP-2v	Grey chalk	76,277	38,08	208,305	2,397851757	**yes**	**yes**
NH-2v	White Chalk	75,727	38,043	174,664	2,029145801	**yes**	no
NH-4h	White Chalk	76,027	37,95	175,342	2,038941007	**yes**	no

Table 1: list of samples for permeability testing

maximum Cell Pressure of 750 kPa has been reached. The pressures used have been kept constant to within a 1 kPa error range.

Each set of pressures will be kept for a time ranging from 15-60 minutes, depending on how long it takes to output an approximately linear time/flow function. The output from the test is the flow through the sample on regular time intervals. These results will be plotted in Matlab to get a Q/t-plot, which will be used to find dQ/dT for every linear section of the graph. Each linear section corresponds with different Cell Pressure/Back Pressure combinations.

Back Pressure (kPa)	Cell Pressure (kPa)	effective pressure (kPa)
150	200	50
250	300	50
350	400	50
450	500	50
550	600	50
650	700	50
700	750	50
720	750	50

Table 2: pressures for permeability testing

Equation to be used for calculating the coefficient of permeability is:

$$k_v = \frac{1.63\ q\ L}{A\{(p_1 - p_2) - p_c\}} \times R_t \times 10^{-4}$$

(BSI,British Standard, 1990) 1)

Where:

Kv = coefficient of permeability (m/s)
L = length of the sample
Pc = pressure loss in the system (kPa)
q = mean rate of flow (mL/min)
(p1-p2) = pressure difference base and top (kPa)
Rt = temperature correction factor for water viscosity

3.1.2 Second set of triaxial permeability tests

After analysing the results from the first few tests, the data was found to be unreliable for grey chalk due to the differential pressure being too low. This will be discussed in section 5.1. Because of this, testing according to the original method was stopped for grey chalk. The four grey chalk samples have been re-tested for permeability because there was not enough time to test all samples again. The samples that have been re-tested have been tested at an effective pressure of 250 kPa, and left to run overnight.

New pressures are shown in table 3.

Back Pressure (kPa)	Cell Pressure (kPa)	effective pressure (kPa)
350	600	250
450	700	250

Table 3: pressures for re-testing of samples

3.2 Brazilian tensile strength test

To test the influence of weathering on the chalk samples, disks of 16mm x 38mm (thickness x diameter) have been made for Brazilian testing. This diameter has been used because in previous BT testing on chalk, the same was used (R.N. Mortimore et al, 2004). The samples have been sketched on tracing paper to record anomalies and ensure proper observation of details in the samples. The samples have been tested under different conditions: dry testing, saturated testing and artificially weathered testing. The artificially weathered samples have been saturated in water first, and then put into vinegar, to speed up the weathering process to achieve 5%, 10%, 15% and 20% mass loss. See table 4 for a list of samples tested.

The tensile strength has been determined by use of the Brazilian tensile strength test, at which the disk-shaped samples are loaded radially, until an extensional crack forms. Data output will be the load on the sample on a regular time interval of 3 seconds. Straight jaws are used. Pictures of the test-setup can be found in figure 4.

Tensile strength will be calculated by the following equation:

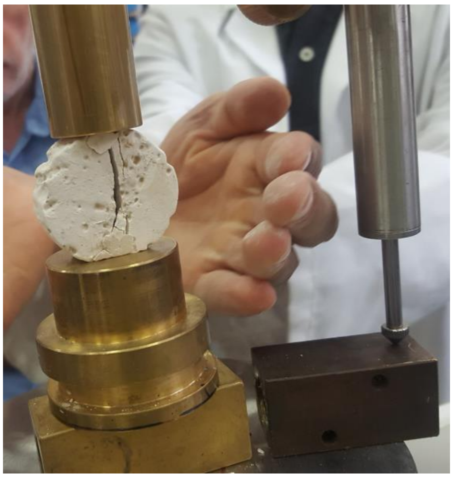
$$\sigma_T = 2P/(\pi DL) \quad 2)$$

In which σ_T is the tensile strength in N/mm^2, P is the applied load in N, D and L are the diameter and length of the sample in mm. Loading rate has been kept constant.

During preparation of the samples, multiple samples have broken. Some due to heating in the oven and some because of being put in a vacuum while submerged in water.

Sample name	Formation	diameter (mm)	thickness (mm)	mass before (g)	mass after (g)	mass loss (%)
V1	white chalk (Seaford)	39,20	16,22	36,694		0
V2	white chalk (Seaford)	39,15	16,03	35,631		0
V3	white chalk (Seaford)	39,12	15,93	35,109		0
V16	white chalk (Seaford)	37,53	15,83	33,489	27,793	2,7
V17	white chalk (Seaford)	37,84	15,90	35,301	29,605	2,8
V18	white chalk (Seaford)	37,87	15,85	35,284	29,588	2,6
V7	white chalk (Seaford)	37,55	15,92	36,168	30,472	5,0
V8	white chalk (Seaford)	37,43	15,72	35,536	29,84	5,0
V9	white chalk (Seaford)	37,46	16,00	35,753	30,057	4,2
V10	white chalk (Seaford)	36,51	15,59	35,542	29,846	10,1
V11	white chalk (Seaford)	36,76	15,66	36,234	30,538	11,3
V12	white chalk (Seaford)	36,72	15,78	35,753	30,057	10,3
V4	white chalk (Seaford)	36,10	15,16	34,482	28,786	15,5
V5	white chalk (Seaford)	37,43	15,24	37,437	31,741	13,8
V6	white chalk (Seaford)	36,14	15,38	35,242	29,546	15,2
V13	white chalk (Seaford)	34,91	14,97	35,42	29,724	19,2
V14	white chalk (Seaford)	35,29	14,70	35,911	30,215	22,3
V15	white chalk (Seaford)	35,15	14,94	35,115	29,419	20,8
V19 (dry)	white chalk (Seaford)	38,28	16,12	30,991		0
V20 (dry)	white chalk (Seaford)	37,94	16,11	28,208		0
Sample name	**Formation**	**diameter (mm)**	**thickness (mm)**	**mass before (g)**	**mass after (g)**	**mass loss (%)**
G1		38,18	16,18	43,47		0
G2	grey chalk	38,26	16,08	43,89		0
G3	grey chalk	38,26	16,14	43,60		0
G12	grey chalk	37,56	15,86	44,839	48,023	5,6
G13	grey chalk	37,54	15,60	43,856	47,101	5,6
G7	grey chalk	36,84	15,45	43,219	44,625	9,9
G10	grey chalk	37,17	15,58	44,191	45,736	9,4
G11	grey chalk	37,04	15,68	44,178	45,568	9,7
G15	grey chalk	35,15	14,94	44,355	43,49	14,8
G16 (dry)	grey chalk	37,53	15,83	42,413		0
G17 (dry)	grey chalk	37,84	15,90	40,191		0

Table 4: list of samples tested for Brazilian Testing



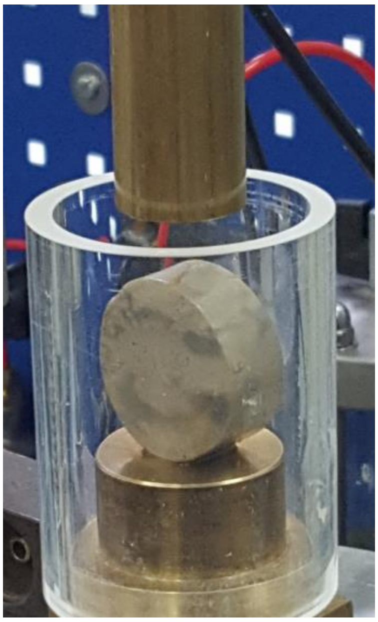


Figure 4: left: Brazilian Testing device. middle: white chalk sample after failure. right: grey chalk sample before failure

3.3 Uniaxial compressive strength test

In the UCS-test, an uniform distributed load will be placed on the top-surface of the samples. Vertical displacement and load will be measured until the sample fails. Data output will be the vertical displacement and load on the sample at regular time intervals.

Upon loading of the sample, the frame will also move, so the resulting total displacement of the samples has to be corrected by the frame displacement. Compliance correction will be done by finding the frame displacements at the load at start of loading, and at the load of failure, and subtracting this:

$$sample\ displacement = \left(displacement(at\ failure) - displacement(\ atstart)\right) - (frame\ displacement(at\ failure\ load) - frame\ displacement(startload))$$

Young's modulus will be calculated by dividing the axial stress at failure by the axial strain.

Table 5 shows a list of the samples tested for UCS, and what treatment they had before testing. Sample 7-15 are samples also used for permeability testing.

Sample	Treatment	Group	Length (mm)	Radius (mm)	Area (m2)	Weight	Density (g/cm3)
1	Dried-salt saturated-dried	Grey Chalk (WMMC)	76,13	18,99	1,133E-03	197,00	2,284
2	salt saturated	Grey Chalk (WMMC)	76,34	19,24	1,163E-03	214,00	2,410
3	salt saturated - dried	Grey Chalk (WMMC)	76,16	19,15	1,152E-03	203,50	2,319
4	dried - salt saturated	Grey Chalk (WMMC)	76,35	19,02	1,136E-03	213,00	2,456
5	dried	Grey Chalk (WMMC)	76,45	19,15	1,152E-03	199,50	2,265
6	water saturated	Grey Chalk (WMMC)	77,45	19,12	1,149E-03	205,60	2,311
7	water saturated	Grey Chalk (WMMC)	78,45	19,19	1,157E-03	208,31	2,295
8	water saturated	Grey Chalk (WMMC)	79,45	19,10	1,145E-03	207,38	2,279
9	water saturated	Grey Chalk (WMMC)	80,45	19,17	1,155E-03	207,78	2,237
10	water saturated	White Chalk (Seaford Chalk)	76,11	19,27	1,167E-03	176,96	1,99
11	water saturated	White Chalk (Seaford Chalk)	76,55	19,34	1,175E-03	178,20	1,98
12	water saturated	White Chalk (Lewes)	76,27	18,84	1,115E-03	171,30	2,01
13	water saturated	White Chalk (Lewes)	75,61	19,12	1,149E-03	172,26	2,02
14	water saturated	White Chalk (Newhaven)	75,73	19,02	1,137E-03	174,66	2,03
15	water saturated	White Chalk (Newhaven)	76,03	18,98	1,131E-03	175,34	2,04

Table 5: list of samples tested for UCS

4. Results

4.1 Triaxial permeability tests results

4.1.1 First set of triaxial permeability tests results

Figure 5 shows the output from the tests. Over the linear sections, dT and dQ have been determined, so the rate of flow can be calculated. Jumps in total flow are caused by changing the pressure.

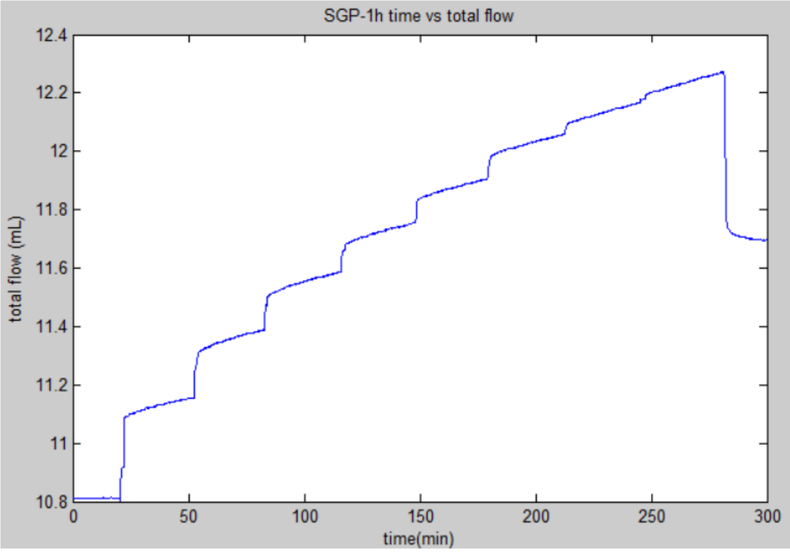


Figure 5: plot of Q/t graph

Table 6 shows the results for the first set of measurements. Not all samples have been tested in this round because the results seemed unreliable for grey chalk. Results will be discussed in section x.x.x.

Sample:	BG-2v	NH-2v	NH-4h	SGP-1h	SGP-2v
Back Pressure (kPa)	Coefficient of permeability (m/s)				
150	2,45E-08	1,12E-08	-	-	-
250	2,43E-08	1,12E-08	1,09E-08	9,02E-11	7,84E-11
350	2,41E-08	1,10E-08	1,10E-08	6,18E-11	4,95E-11
450	2,41E-08	1,07E-08	1,10E-08	4,41E-11	3,83E-11
550	2,38E-08	1,06E-08	1,10E-08	3,81E-11	3,47E-11
650	2,39E-08	1,06E-08	1,09E-08	3,11E-11	3,09E-11
700	2,38E-08	1,02E-08	1,09E-08	3,13E-11	3,33E-11
720	2,38E-08	1,03E-08	1,09E-08	3,08E-11	3,01E-11

Table 6: first round permeability results

4.1.2 Second set of triaxial permeability tests results

During the second round of testing, only the grey chalk has been tested. Results are shown in table 7.

Sample	coefficient of permeability (m/s)			
BP (kPa)	SGP-2V	SGP-1V	SGP-2h	SGP-1h
350	1,50E-11	1,69E-11	1,95E-11	2,63E-11
450	1,32E-11	2,05E-11	1,58E-11	1,63E-11

Table 7: second round permeability results

4.2.1 Brazilian Tensile Strength Test Results

Each of the Brazilian Tests done provides us with a graph as shown in figure 6. The first major drop in load has been taken as the failure point, because this is the point the sample cracks. The other peaks are just from continuous loading after the first failure.

This failure point has been determined for each of the tested samples, and results are displayed in figure 7 and figure 8. These results will be discussed in section 5.2. They are based on data from table 8.

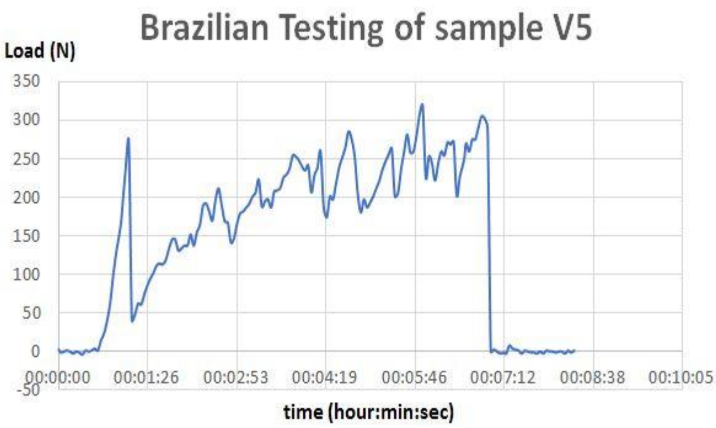


Figure 6: result of BT test of sample V5

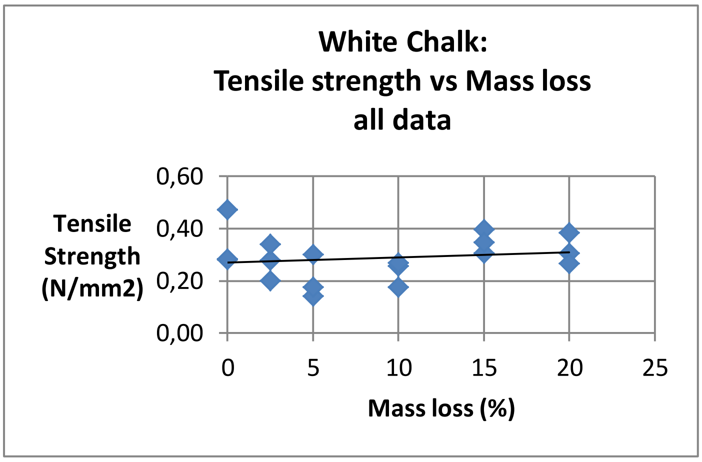


Figure 7: white chalk results all data

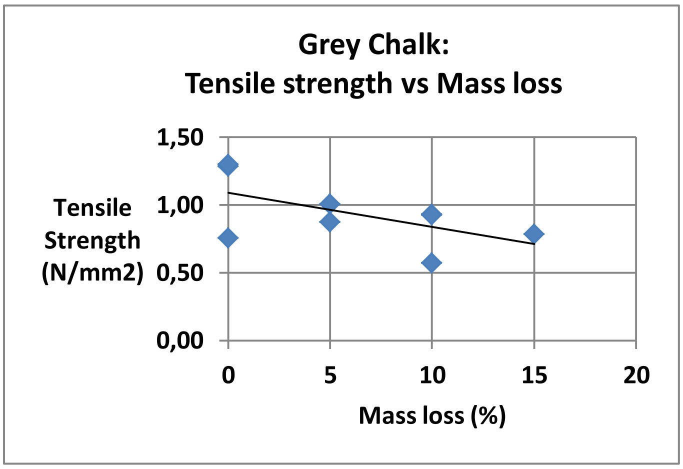


Figure 8: grey chalk results all data

Sample name	Failure load (N)	tensile strength (I	average strength (N/mm2)	Sample name	Failure load (N	tensile strength (N/mm2)	average strength (N/mm2)
V1	280,5	0,28	0,34	G1	730,713	0,75	1,11
V2	463,5	0,47		G2	1242,318	1,29	
V3	275,3	0,28		G3	1257,91	1,30	
V16	259,4	0,28	0,27	G12	818,036	0,87	0,94
V17	187,9	0,20		G13	925,787	1,01	
V18	320,4	0,34		G7	511,585	0,57	0,81
V7	282,1	0,30	0,21	G10	846,577	0,93	
V8	128,9	0,14		G11	843,996	0,93	
V9	165,3	0,18		G15	646,627	0,78	1,41
V10	154,9	0,17	0,23	G16 (dry)	1898,35	2,03	
V11	230,2	0,25		G17 (dry)	2554,033	2,70	
V12	243,2	0,27					
V4	339,3	0,39	0,35				
V5	273,0	0,30					
V6	302,9	0,35					
V13	315,2	0,38	0,32				
V14	249,0	0,31					
V15	219,1	0,27					
V19 (dry)	379,1	0,39	0,45				
V20 (dry)	492,1	0,51					

Table 8: Brazilian Testing results

4.3.1 UCS Strength Test Results

Figure 9 shows the result for the UCS strength test for an arbitrary sample, sample 3. Similar graphs have been made for all 9 UCS tests. Peak load has been read from the data and the associated stress has been calculated and documented. Young's modulus has been calculated from the stress and the strain which has been calculated out of the linear part of the stress/strain graph. All of the results can be found in table 9.

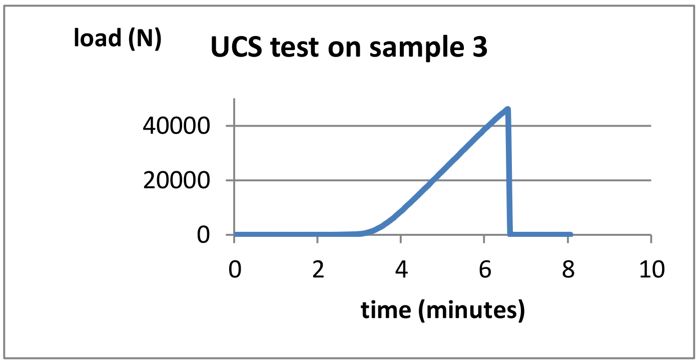


Figure 9: UCS test output for sample 3

Sample	Treatment	Group	maxload (N)	Max stress (MPa)	Young's Modulus (gPa)
1	Dried-salt saturated-dried	Grey Chalk (WMMC)	33169,106	**29,28**	**6,9**
2	salt saturated	Grey Chalk (WMMC)	18174,246	**15,63**	**2,8**
3	salt saturated - dried	Grey Chalk (WMMC)	46034,276	**39,96**	**14,8**
4	dried - salt saturated	Grey Chalk (WMMC)	32837,928	**28,91**	**10,7**
5	dried	Grey Chalk (WMMC)	45854,860	**39,80**	**12,1**
6	water saturated	Grey Chalk (WMMC)	20280,857	**17,66**	**3,1**
7	water saturated	Grey Chalk (WMMC)	16624,245	**14,37**	**2,3**
8	water saturated	Grey Chalk (WMMC)	14186,455	**12,38**	**2,4**
9	water saturated	Grey Chalk (WMMC)	20175,109	**17,47**	**2,7**
10	water saturated	White Chalk (Seaford Chalk)	2809,835	**2,41**	**2,9**
11	water saturated	White Chalk (Seaford Chalk)	3686,677	**3,14**	**4,1**
12	water saturated	White Chalk (Lewes)	4097,007	**3,68**	**3,5**
13	water saturated	White Chalk (Lewes)	5004,62	**4,36**	**3,5**
14	water saturated	White Chalk (Newhaven)	3569,809	**3,14**	**2,3**
15	water saturated	White Chalk (Newhaven)	4016,506	**3,55**	**1,8**

Table 9: UCS test results

5. Discussion

5.1 Triaxial permeability test discussion

The permeabilities found with this set of tests are reliable for white chalk but unreliable for grey chalk. It seems that the grey chalk samples are so dense and clayey that an effective pressure of 50 kPa is not enough to force the water through the sample, and instead it flows between the membrane and the sample because the permeability of the sample is so low. It also takes a long time for the flow to become linear, so testing for longer periods of time is preferred. Because of this we decided to stop testing grey chalk at this pressure, and instead, test at higher effective pressure for an extended amount of time.

The general trend of the permeability for both sets of tests does show slight increases in permeability for the horizontal samples, however the small difference that there is, is not enough to be significant because the variance in the results is too big to say for certain that there is anisotropy. Further testing on more samples has to be done to confirm it.

5.2 Brazilian Tensile Strength Test Discussion

When doing the Brazilian Testing on the samples, a downward slope in the mass-loss/tensile strength graph is expected because weathering causes weakening of rock. The grey chalk behaved according to expectations. However the white chalk shows strengthening of the sample at 15% and 20% mass loss, instead of weakening.

Analysis of pictures of the sample before testing shows us that the white chalk at higher percentage mass-loss has chipped significantly around the edges from the weathering, causing the radial surface to deform severely. The grey chalk remained its disc shape. The chipping of the white chalk caused an increase in contact area between the load and the sample, causing the stress caused by a certain load to decrease. This makes the sample's tensile strength to appear higher than it actually is. Therefore, the 15% and 20% tests for white chalk have been excluded. 10% mass loss also needs to be excluded as it is chipped enough to not be reliable anymore. Figure 10 and 11 show the results of the Brazilian testing on the white chalk up until 10% and 5%. For pictures of the samples after mass-loss, see Appendix C.

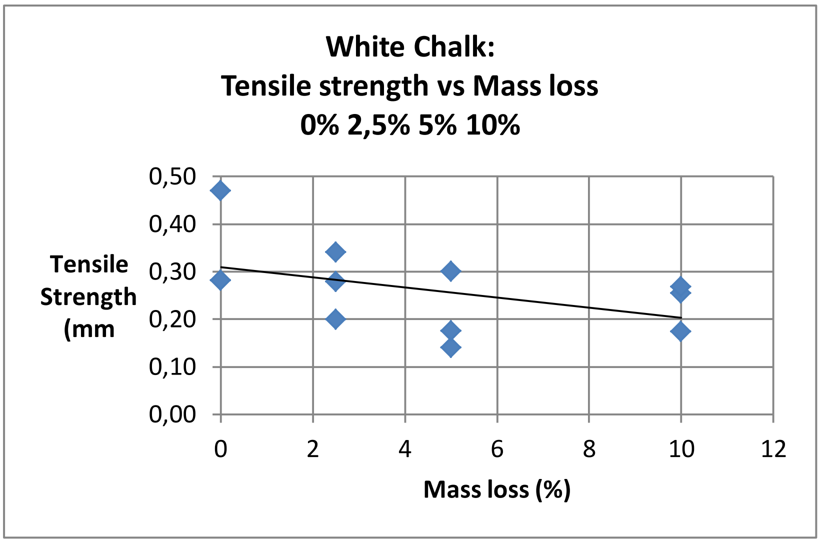


Figure 10: white chalk 0%, 2,5%, 5%, 10% mass loss

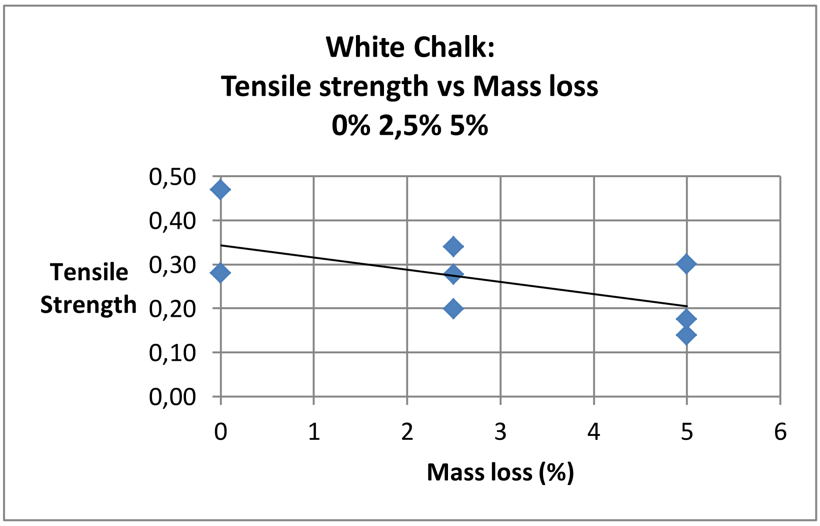


Figure 11: white chalk, 0%, 2,5% 5% mass loss

5.3 UCS Strength Test Discussion

The salt water saturation showed no lowering of the strength of grey chalk. If anything, it shows an increase in UCS strength over the samples that were only water-saturated. This is the opposite result of what has been found for white chalk, which weakened significantly (J.A. Lawrence et al, 2013). However, it must be said that the research done in 2013 has been way more extensive, with way more samples, so is statistically more relevant.

6. Recommendations

Further research on the weathering scenarios needs to be done. The initial results are interesting because of the different effect the saltwater-cycles have on white and grey chalk, but this needs to be repeated on a bigger scale. A bigger number of grey chalk samples need to be tested so the results can be backed up by more data and be statistically relevant.

Access to a SEM microscope would have improved the understanding on what exactly is happening within the structure of the samples upon weathering, making this a must for any further research into the topic because now we can only guess what happened within the sample, and SEM microscope images would show us what changes the weathering made to the structural integrity of the rock.

7. Conclusion

Is there anisotropy in the permeability of the chalk samples?

For the grey chalk, based on the results from the second round of permeability tests we cannot say with certainty that there is anisotropy in permeability. If we take the average of the horizontal and vertical measurements, $1{,}64*10^{-11}$ m/s for vertical and $1{,}95*10^{-11}$ m/s for horizontal, it does seem like the horizontal permeability is slightly bigger than the vertical permeability. However, if you look at the variance in permeability results, this is not conclusive enough to say for sure that there is permeability. A possible explanation for the lack of anisotropy could be the complex geological history of chalk. Recrystallization and solution/precipitation of $CaCO_3$ in pore fluid could be the cause of it, but further research would have to be done by SEM Microscope to see if this is the case, and more extensive testing on more samples should be done.

How does chemical weathering by dissolution affect the tensile strength of the chalk?

The Brazilian Test results show a clear downward slope in the tensile strength of the chalk samples. Tensile strength has decreased by 43% strength loss for white chalk at 5% mass loss, whereas at the same mass loss percentage the grey chalk only drops 15% in strength. This shows that the white chalk subgroup is more affected, and loses significant strength when weathered.

How does evaporation of salt water from the sample, and the associated forming of salt crystals, affect the uniaxial compressive strength of the chalk?

The grey chalk did not show any weakening from salt water, and instead showed slight increases in strength from salt water evaporating inside of the sample. This is not what was expected based on results from previous research on white chalk. What can be concluded from this result, is that chalk as found in the cliffs should not be seen as 1 big rock mass, but that instead different subgroups have very different properties and reactions to weathering mechanisms and that each subgroup should be approached differently.

Is there a relation between the unweathered chalk's tensile- and compressive strength? And if so, can this be extrapolated to the weathered samples?

Unfortunately due to the limited time available and samples breaking during preparation, only a small amount of samples have been tested. Partially because of the limited amount of data and partially because of the results being too spread-out, we have been unable to obtain any correlation between the tensile strength and the UCS.

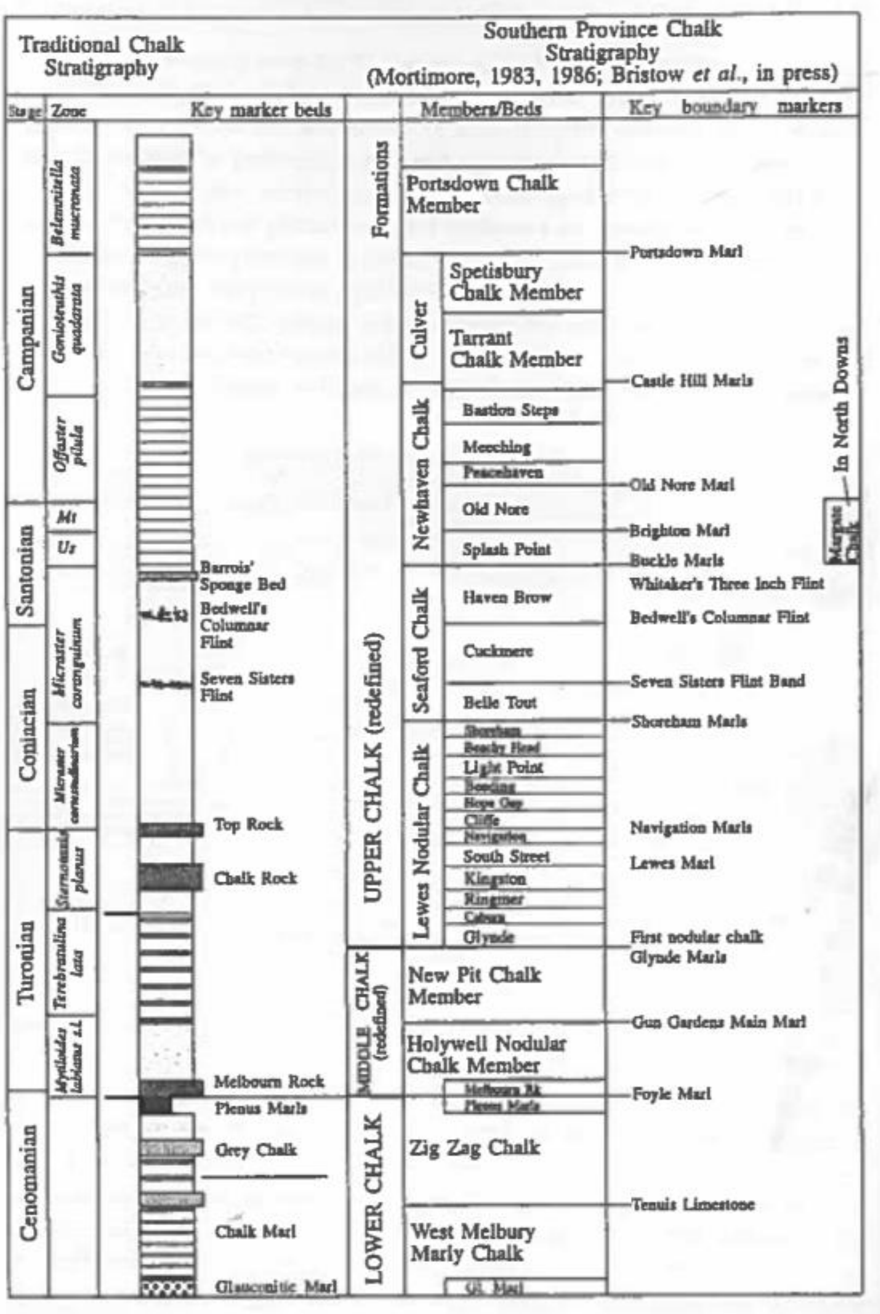
How can we apply these results to further the understanding of coastal chalk cliff collapse?

What has been found is that different formations within the chalk have very different strength properties, and the chalk cliffs should not be seen as 1 rock mass, identical at every location. The grey chalk responds very different to weathering than the white chalk. The study of chalk has been going on for many years, and it will be studied continually over the years to come. These results should be seen as one of the bricks that lay the foundation for further research. Getting an understanding of the engineering properties of the different formations within the chalk will benefit further research into the failure mechanisms, strength of the rock mass and eventually to developing ways to counter cliff collapse.

Reference list

1) Mortimore, R.N., Wood, C.J. & Gallois, R.W. (2001) *Geological Conservation Review Volume No. 23 (2001)* Chapter 3: Southern Province, England p1
2) British Geological Survey, http://www.bgs.ac.uk/lexicon/lexicon.cfm?pub=WMCH
3) British Geological Survey, http://www.bgs.ac.uk/lexicon/lexicon.cfm?pub=SECK
4) British Geological Survey, http://www.bgs.ac.uk/lexicon/lexicon.cfm?pub=NCK
5) British Geological Survey, http://www.bgs.ac.uk/lexicon/lexicon.cfm?pub=LECH
6) BSI, British Standard 1377-6: 1990, *Methods of test for Soils for civil engineering purposes*
7) R.N. Mortimore, K.J. Stone, J. Lawrence & A. Duperret. (2004) *Chalk physical properties and cliff instability*
8) Cianta, M.O. (2013), *Multiscale hydro-chemo-mechanical modelling of the weathering of calcareous rocks: an experimental, theoretical and numerical study*
9) J.A. Lord, C.R.I. Clayton, R.N. Mortimore (2002) *Engineering in Chalk*
10) J.A. Lawrence, R.N. Mortimore, K.J. Stone, J.P. Busby (2013), *Sea saltwater weakening of chalk and the impact on cliff instability*
11) A. Duperret, A. Genter, A. Martinez, R.N. Mortimore (2004) *Coastal chalk cliff instability in NW France: role of lithology, fracture pattern and rainfall*
12) R.N. Mortimore (1997), *The Chalk of Sussex and Kent*

Appendix A: Chalk stratigraphy used by the BGS. (R.N. Mortimore, 1997)

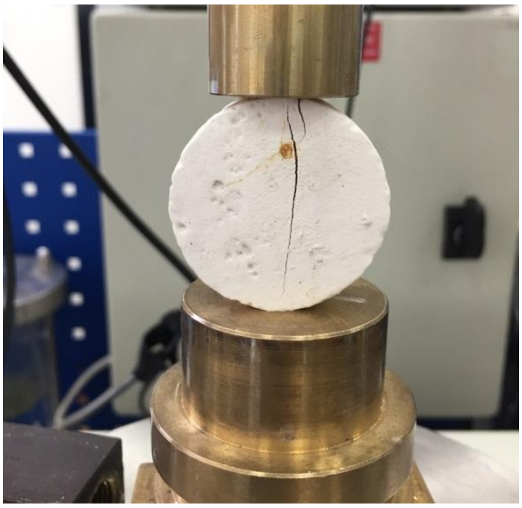


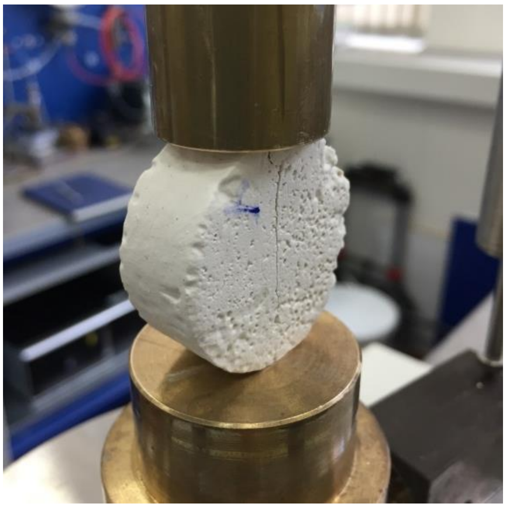
Appendix B: full list of samples prepared for permeability testing

Sample	Formation	height (mm)	diameter (mm)	weight (g)	Density (g/cm3)	tested and analysed	tested in second round
BG-1v	White Chalk	76,11	38,54	176,96	1,99	no	no
BG-2v	White Chalk	76,25	38,36	176,96	2,01	**yes**	no
BG-1h	White Chalk	76,55	38,68	178,20	1,98	no	no
HG-1v	White Chalk	76,27	37,67	171,30	2,01	no	no
HG-4h (?)	White Chalk	75,61	38,24	172,26	1,98	no	no
SGP-1v	Grey chalk	76,60	38,19	205,60	2,34	no	**yes**
SGP-1h	Grey chalk	76,73	38,34	207,38	2,34	no	**yes**
SGP-2h	Grey chalk	76,85	38,38	207,78	2,34	**yes**	**yes**
SGP-2v	Grey chalk	76,28	38,08	208,31	2,40	**yes**	**yes**
NH-2v	White Chalk	75,73	38,04	174,66	2,03	**yes**	no
NH-4h	White Chalk	76,03	37,95	175,34	2,04	**yes**	no

Appendix C: Brazilian Testing sample pictures after mass-loss

White Chalk (Seaford Chalk), 10% mass loss, sample V11:





White Chalk (Seaford Chalk), 15% mass loss, sample V6:

White Chalk (Seaford Chalk), 20% mass loss, sample V20:

Grey Chalk (WMMC), 5% mass loss, sample G14:

Grey Chalk (WMMC), 15% mass loss, sample G15:

Pictures by: Yunchaun Li