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The Effect of Quartz and Feldspar Minerals on Formation of Bentonite Filter Cake over Gneissic Bedrocks in Sri Lanka

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Abstract: Bentonite is used as a drilling agent for deep foundation engineering works. Bentonite slurry gives stability to pile walls during the drilling operation by creating a layer called 'filter cake' or 'mud cake'. However, there is evidence that Bentonite filter cake reduces the shear strength capacity of soil-concrete and rock-concrete interfaces since it prevents direct contact of soil and concrete, or rock and concrete. Several studies have been carried out both empirically and experimentally in order to find the characteristics of filter cake formation over soil surfaces. According to the studies, formation of Bentonite filter cake has been studied on rocks such as sandstones and mudstones but not on metamorphic rocks. Thus, the current study investigated the formation of Bentonite filter cake on metamorphic rock samples using a specially designed pressure chamber. This paper presents the influence of major mineral constituents of a few selected Gneissic rock types on the formation of Bentonite filter cake. During the initial investigations of this study, it was found that a Bentonite filter cake of about 4mm thick was formed under a constant slurry pressure of 3 bar during a 12-hour exposure time. It was also found that there is no influence on Bentonite filter cake formation by major mineral constituents: Feldspar and Quartz.

Keywords: Bentonite filter cake, Metamorphic rock, Pressurechamber, XRD analysis

1. Introduction

Usage of Bentonite based slurries for foundation engineering works has been outlined by many researchers. Loss of fluid in Bentonite slurry forms an impermeable layer called filter cake. It is used as one of the primary applications in the drilling industry to seal porous side walls of drilled holes with a mud layer [1]. Bentonite slurry penetrates permeable surfaces until the gel strength of the slurry acts over the penetrated area of soil particles to prevent further penetration [2]. Formation of filter cake is essential for stable excavation. However, it has been found that a considerable reduction in the skin friction of friction piles occurs due to the filter cake layer that continues to remain between pile concrete and soil interfaces [3].

The formation of filter cake over rock sockets has been explored by many investigators [4, 5, 6, 7]. They found a significant reduction in the skin friction capacity of rock-concrete interfaces due to Bentonite filter cake formation. Therefore, some best practice guidelines were introduced to avoid the effect of Bentonite filter cake on the skin friction capacity of rock-concrete interfaces [7]. Some researchers have investigated the shear behaviour of rock-concrete interfaces in the presence of Bentonite filter cake using Constant Normal Stiffness (CNS) direct shear apparatus [8]. Such studies have proved the reduction of skin friction capacity of rock-concrete interfaces when the filter cake thickness exceeds its threshold limits.

Crystalline metamorphic rocks are present in most places in Sri Lanka where Cast In-situ Bored (CIB) piling is carried out. These possess higher values for Uniaxial Compressive Strength (UCS), Rock Quality Designation (RQD) and Core Recovery(CR) compared to the rocks of sedimentary origin [9]. Nevertheless, in Sri Lanka, most foundation designers neglect the strength of bedrock when calculating the skin friction capacity of bedrock [9]. Unfractured igneous rocks and metamorphic rocks have the lowest permeability of all rock types.

Therefore, it has been predicted that metamorphic rocks do not support Bentonite filter cake formation by means of surface filtration unlike sedimentary rocks. This paper presents laboratory experiments that study the

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formations of Bentonite filter cake over Gneissic rocks. However, during the initial investigations of this study, it was found that a Bentonite filter cake of about 4 mm thick was formed under a slurry pressure of 3 bar during a 12-hour exposure time. Therefore, the mechanism of Bentonite filter cake formation over Gneissic metamorphic rocks was investigated by analysing the mineralogical compositions of the respective rocks. This paper presents the results obtained after performing X-ray diffraction (XRD) analysis on Gneissic rocks.

2. Laboratory Simulation for Filter Cake Formation on Rocks

Simulation for filter cake formation on permeable rock sockets has been carried out by means of a filter press in several studies related to the oil industry [3, 10, 11, 12]. It had also been widely used by researchers engaged in piling and diaphragm wall construction [7, 13, 14, 15]. However, the shortcomings of using a filter press as a tool for measuring the filter cake characteristics have been outlined [16, 17]. Accordingly, the adoptability of the Laboratory Filtration Theory has been assessed by considering the Filtration Theory of Phillip &Smiles [18] and the results of the other researchers [10, 11]. It can be concluded that experiments carried out on a filter press constitute a reasonably accurate method in simulating the filter cake formation over intact rock surfaces under the following conditions:

1. The permeability of the intact rock (K_{intact}) is considerably greater than the permeability of the filter cake particle matrix (K_{e1}) at the void ratio that is produced for matrix stress equal to the applied filtration pressure.
2. The intact rock permeability is adequately low to ensure that surface filtration occurs.
3. The filtration pressure driving filtration is established comparatively fast and continued at an approximately constant level.
4. Filter cake formation in the field is analogous to static filtration [19].

The experimental data of Meeten & Sherwood [11] in evaluating the significance of condition 1 for a pure Bentonite slurry which is filtered at a filtration pressure of 15 kPa (equivalent to about 1.5 m filtration head) and Ke_1 was found to be equivalent to a hydraulic conductivity of approximately 10^{-10} ms^{-1}[19]. According to the typical rock permeability values [20], condition 1 is fulfilled for most limestones, sandstones, and permeable volcanic rocks. Further, surface filtration mentioned in condition 2 can occur in materials with permeability up to that of coarse-grained soil and a slurry containing some sand particles [4]. Therefore, a properly constituted slurry is likely to experience surface filtration in most of permeable rock layers. According to Wates &Knight [14], filter cake formation is independent of the rock permeability if the conditions 1 and 2 are satisfied. However, conditions 1 and 2 are not met for metamorphic rocks due to their dense crystalline grain arrangement. No research studies have been carried out so far to study filter cake formation over crystalline metamorphic rocks. Thus, in the current study, a specially built pressure chamber was used to provide field conditions for selected Gneissic rock samples.

2.1 Development of Pressure Chamber

Several researchers investigated the effects of polymer and Bentonite support fluids on concrete-sand interface shear strength by means of a specially built direct shear apparatus [3]. Prior to conducting direct shear tests, the shear boxes used for the aforementioned studies enabled filtration by applying Bentonite slurry pressure on the sand surface. For the current study, dimensions of the lower and upper halves of shear boxes of direct shear apparatus used by Lam et al. [3] were used to develop the pressure chamber. However, filtration was not allowed in the pressure chamber as permeability is considered negligible in metamorphic rocks unlike in previous research studies. Accordingly, the pressure chamber was built as shown in Figure 1. Two halves of the pressure chamber were attached to each other by nuts and bolts after placing the rock sample in the lower half. The chamber is made slurry tight by a 10 mm thick rubber spacer. Further, Bentonite slurry pressure was generated by means of a pressure pump with a non-return valve which is fixed to the upper half of the pressure chamber. The cell pressure was measured by means of a pressure gauge which has the least count of 0.05 MPa.

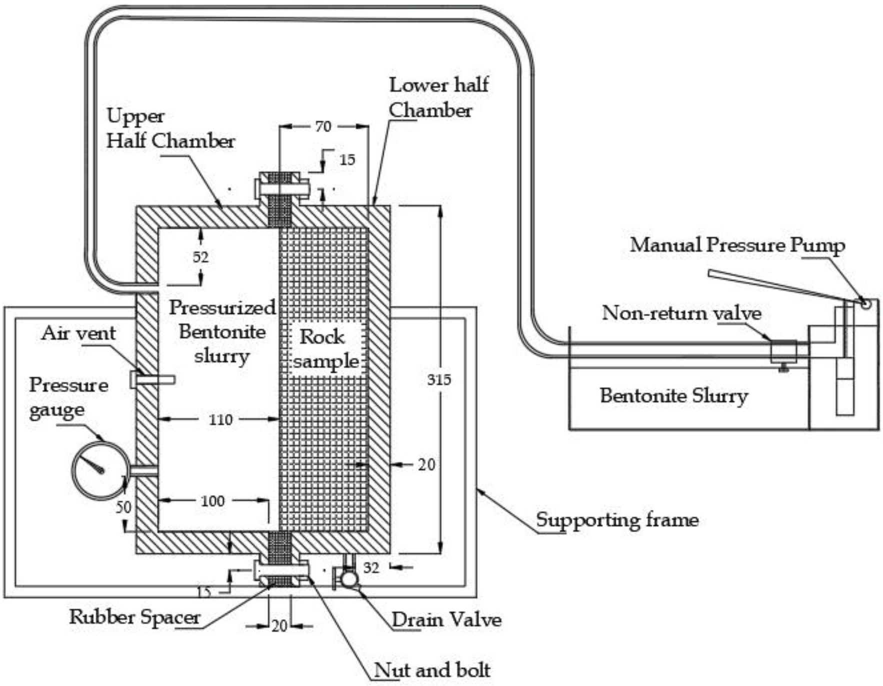

Figure 1 - Pressure Chamber

2.2 Investigation of the Formation of Filter Cake over Gneissic Rocks

A questionnaire survey was circulated among the leading piling contractors in Sri Lanka. It was found that the most commonly encountered average depth range of piles was between 20 m to 30 m. By considering the upper limit of the depth range, a constant slurry pressure of 3 bars was applied to the pressure chamber. The constant pressure was maintained by continuous monitoring of the pressure gauge and making minor pressure changes as required using the manual pressure pump. Additionally, the pressure chamber was fitted with a non-return valve to avoid pressure drops inside the chamber.

Further, the questionnaire-survey revealed the most commonly encountered duration between the termination of drilling and the beginning of concreting as 3 - 6 hours. In the present work, the slurry pressure was applied up to 12 hours to simulate the worst condition and to compare the results meaningfully with the literature. For this work, 11 Gneissic rock samples from 4 rock types and 3 weathering grades were sized into cuboids which have the dimensions of 275 mm length, 175 mm breath, 75 mm height and a JRC roughness value of 0 to 2 on the surfaces (indicating smooth surfaces) [21] as shown in Figures 2 and 3.

Subsequently, pressure was applied to the rock samples for time durations of 1 h, 2 h, 3 h, 6 h, and 12 h, and the mean filter cake thicknesses were obtained by means of a Spherometer.

Figure 2 - Rock Sample of Garnet Granulite Gneiss

Figure 3 - Rock Sample of Biotite Gneiss

3. The Effect of Mineralogical Composition on Bentonite Filter Cake Thickness

Since filtration was not allowed in this experiment, the reasons for the formation of Bentonite filter cake should be investigated. Gneisses mostly comprise Quartz and Feldspar minerals. Minerals such as Biotite, Hornblend, Hypersthene, Garnet, etc. are also present in different proportions in Gneisses.

In this work, four (4) rock types were used: Biotite Gneiss, Garnet Granulite Gneiss, Quartzofeldspathic Gneiss, and Charnokitic Gneiss. These rocks were of three weathering grades: Grade 1- Fresh Rock, Grade 2- Slightly Weathered, and Grade 3 – Moderately Weathered.

3.1 XRD Spectrometer Analysis

Sections of uniform thickness were cut from the Gneissic rock samples in the direction perpendicular to foliations in such a way that all minerals in each foliation were represented approximately equally. Next, the samples were ground to obtain the representative powder sample using an AIV apparatus. The powdered samples were passed through a 50-micron sieve. About 50 g of powdered samples of each rock type were collected. Subsequently, all the samples were analysed using the Rigaku Ultima-iv XRD spectrometer which has a Cu x-ray tube that generates waves that have the wavelength of 1.54059292 Å. The diffraction angle 2θ was changed from 3° to 83° at 2° per minute. Raw data were obtained and analysed by means of Match 3 program and phases were matched and refined. The spectrum with matched peaks obtained for the Biotite Gneiss is shown in Figure 4. All the major minerals of Gneisses were detected while a few minor minerals were not detected due to mismatches of peaks. Visual observations by a geology expert confirmed the availability of minor minerals in the collected samples. The percentages of mineral compositions were obtained using the reference intensity ratio method. This is detected automatically in Match 3 software, and it gives a fairly acceptable quantitative analysis. Table 1 shows the composition of major minerals and the corresponding Bentonite filter cake thickness.

Table 1 - Mineralogical Composition of Gneisses and Their Filter Cake Thicknesses

Rock Type and weathering grade		Quartz (%)	Feldspar (%)	Filter cake Thickness (mm)
Biotite Gneiss	1	24.5	56.0	1.97
	2	26.8	58.9	2.97
	3	29.1	61.7	3.06
Quartzofeldspathic Gneiss	1	24.0	55.2	2.21
	2	23.3	76.7	3.97
	3	16.7	74.7	4.15
Charnokitic Gneiss	1	59.3	34.0	2.33
	2	23.3	61.4	3.91
Garnet Granulite Gneiss	1	35.8	51.8	2.36
	2	71.6	24.1	2.55
	3	42.8	31.6	3.61

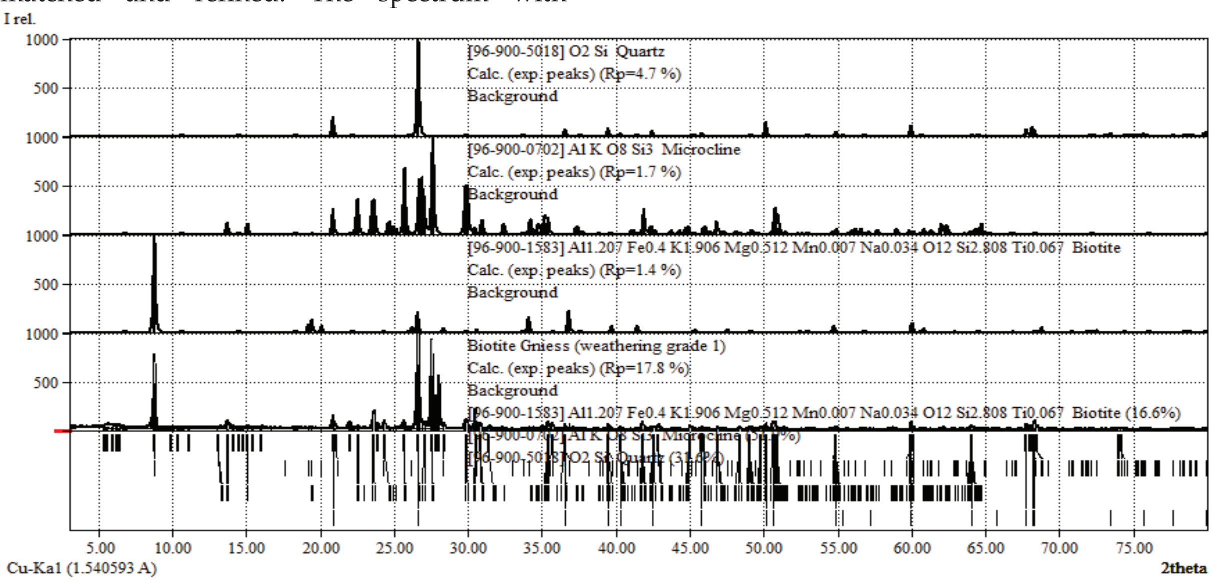

Figure 4 - XRD Pattern for Biotite Gneiss Weathering Grade 1

During the entire weathering process, the quartz content may remain similar though the feldspar may alter to clay. According to Table 1, the Quartz content of each rock type changes considerably when it is weathered. One possible reason for this observation is, weathering Grade 1 (fresh rock) of each rock type was obtained from deeper levels and weathering Grade 2 and Grade 3 were obtained from shallower depths from the same locations. Therefore, there is a possibility of slight variations in the overall mineralogical contents of the same rock type irrespective of the weathering grade, due to the depth of formation of rock. Nevertheless, the Quartz content change in Charnokitic Gneiss and of weathering Grade 2 of Garnet Granulite Gneiss give apparently unrealistic values which may have occurred due to anomalies in the sample collection and the XRD analysis.

4. Results

The variation of filter cake thickness for weathering Grade 3 of three Gneissic rock types is shown in Figure 5. The curves fitted on data were generated by logarithmic regression analysis. From testing, the maximum filter cake thickness found was at 4.15 mm after 12 h for Quartzofeldspathic Gneiss.

R^2 values for all the curves generated are above 0.85 and the level of significance of all the models is over 98%. Consequently, the models represent the readings well and Bentonite filter cake thicknesses for these rock samples can be predicted between the range of 1 h to 12 h using these models.

Further, the Pearson coefficient (PC) correlations for Quartz Content Vs Bentonite filter cake thicknesses and Feldspar Content Vs Bentonite filter cake thicknesses were obtained as shown in Table 2. The PC should be within -1 and -0.5 for good negative correlations and within 1 and 0.5 for positive correlations.

According to Table 2, the Pearson coefficient for the correlation between the Quartz content and the Bentonite filter cake thicknesses is -0.386 which is greater than -0.5 and hence there is a weak correlation. The correlation between Feldspar content and Bentonite Filter cake thicknesses has a Pearson coefficient of 0.482 which is slightly less than 0.5 and hence, there is a weak correlation.

Since it shows weak correlations for both cases, results of the 2-tailed test were used to find the significance of the correlation coefficients.

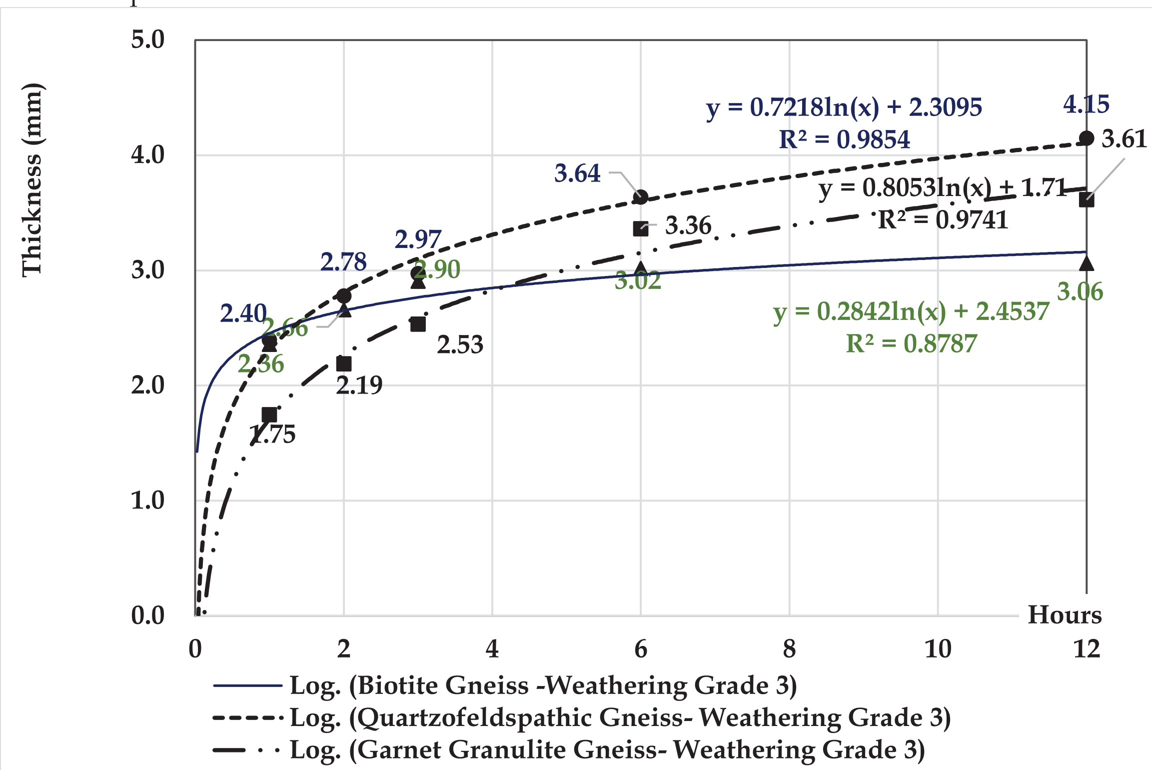

Figure 5 - Variation of Bentonite Filter Cake Thickness with Time for 3 Gneissic Rock Types of Weathering Grade 3

Table 2 - Correlation Analysis: Quartz Content Vs Bentonite Filter Cake Thickness and Feldspar Content Vs Bentonite Filter Cake Thickness

Correlations		Quartz	Bentonite Filter Cake Thickness
Quartz	Pearson Correlation	1	-0.386
	Sig. (2-tailed)		0.241
		Feldspar	Bentonite Filter Cake Thickness
Feldspar	Pearson Correlation	1	0.482
	Sig. (2-tailed)		0.133

H_0 = There is no correlation between the mineral content and the Bentonite filter cake thickness; $P > 0.05$
H_1 = There is a correlation between the mineral content and the Bentonite filter cake thickness; $P < 0.05$

Since P is greater than 0.05 in both cases, the correlation between the mineral content and the Bentonite Filter cake thickness is insignificant. Therefore, the null hypothesis is accepted and hence, there is no correlation between the mineralogical content and the Bentonite filter cake thickness. Even though the null hypothesis is accepted in above correlations, PC of the Feldspar content and the Bentonite filter cake thickness is approximately equal to 0.5. Therefore, a scatter plot obtained by the percentages of Quartz and Feldspar in 11 Gneissic rock samples were analysed against the filter cake thickness by a linear regression model to draw any association between the mineral compositions and the Bentonite filter cake thickness. The linear regression model generated for the Quartz content and Feldspar content with the correspondent Bentonite filter cake thicknesses is shown in Figures 6 and 7, respectively.

According to Figures 6 and 7, Bentonite filter cake thickness shows a positive linear variation with Feldspar content and negative linear variation with Quartz content. However, these graphs have small R^2 values which show a wider distribution of thickness values from the generated linear models. The level of significance of the generated linear models and their gradients and intercepts are shown in Table 3. According to Table 3, the significance of the Quartz Content Vs Bentonite filter cake thickness, and Feldspar Content Vs Bentonite filter cake thickness are 0.241 and 0.133, respectively. From Two T test, the hypothesis was rejected for the model of Quartz Content Vs Bentonite filter cake thickness and the model of Feldspar Content Vs Bentonite filter cake thickness at 95% confident level. Further, the gradients of both models which have values of 0.022 and -0.018, respectively, for the model created for Feldspar and Quartz are approximately equal to zero which show that there is almost no association between the Bentonite filter cake thickness and Quartz and Feldspar contents.

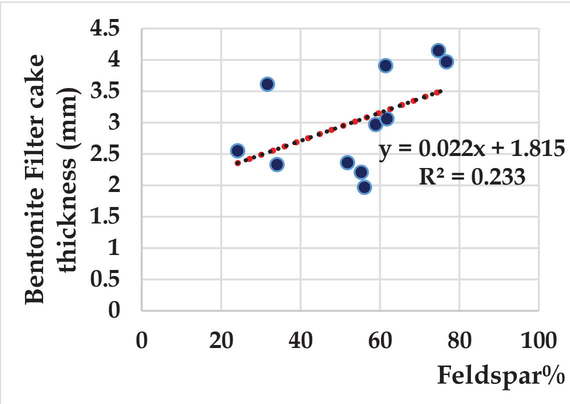

Figure 6 - Feldspar Content Vs Bentonite Filter Cake Thickness

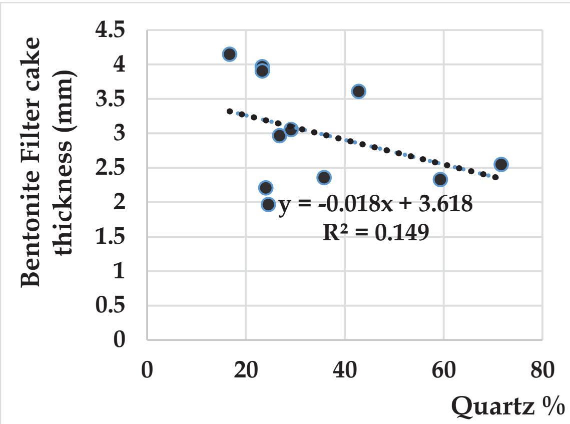

Figure 7 - Quartz Content Vs Bentonite Filter Cake Thickness

Table 3 - Details of the Models Generated for Bentonite Filter Cake Thickness Vs Quarts and Feldspar Contents

Linear Model	Model Equation	R^2	Model Significance	Coefficient Significance	Intercept Significance
Quartz content Vs Bentonite Filter Cake Thickness	Y = -0.018(x) + 3.618	0.149	0.241	0.000	0.241
Feldspar Content Vs Bentonite Filter Cake Thickness	Y = 0.022(x) + 1.815	0.233	0.133	0.004	0.133

5. Conclusion

According to the results obtained by the Pearson correlation analysis and the linear regression models, Bentonite filter cake thicknesses show almost no association with Quartz content and Feldspar content. Nevertheless, weathering Grade 3 of Quartzofeldspathic Gneiss showed the highest Bentonite filter cake thickness of about 4.15 mm after 12 hours under a slurry pressure of 3 bars, irrespective of the Quartz and Feldspar contents.

Some samples which had approximately equal mineral contents showed different filter cake thicknesses (weathering Grade 1 of Biotite Gneiss and weathering Grade 1 of Quartzofeldsphatic Gneiss). The presence of micro fissures and their orientation may affect surface filtration [7]. In that case, Bentonite filter cake thickness may vary even though mineralogical contents are approximately similar. Moreover, these samples are from different rock types though mineral contents are approximately similar. Therefore, the presence of other minerals apart from Quartz and Feldspar, and their grain arrangement may affect the formation of filter cake.

Further, linear regression models generated for Quartz and Feldspar Contents Vs Bentonite filter cake thickness give nearly flat trend lines with very small gradients. It confirms the poor association between the mineralogical content vs the thickness of Bentonite filter cake. Moreover, by these results, it can be concluded that Quartz and Feldspar contents have no influence on the formation of Bentonite filter cake over the selected Gneissic rock types of this work.

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