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Rheological properties of cement-stabilised kaolin

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ABSTRACT

Deep soil mixing is a process used to improve the mechanical properties of soft soils by mixing dry or wet binders with the existing soil. The strength and deformation properties of the treated soils depend on the initial soil conditions, the type and amount of binder used and the curing conditions. The homogeneity and strength of soils stabilised by deep mixing also depend on the mixing mechanisms that occur during construction. These mixing mechanisms are directly related to the rheological properties of the materials being mixed. Therefore, rheology is the starting point in understanding the processes involved in deep soil mixing although knowledge of the rheological characteristics of stabilised clays is very limited. The aim of the research presented in this paper is to investigate the effects of cement stabilisation on the rheological properties of kaolin clay. The flow properties of kaolin, cement slurries and kaolin-cement mixtures at various moisture contents were measured using a rheometer with two different geometries: parallel plates and the ball measuring system. For all mixtures tested, the shear stresses increase as the moisture content decreases. A good agreement was found between the stresses measured using the parallel plates and the ball measuring system for kaolin suspensions, validating the use of this shear geometry for subsequent studies on coarse grained soils. The results are discussed with respect to in situ soil mixing processes. It is proposed that observations made in the field on the relation between blade rotation speed and strength and homogeneity of treated soils can be explained by the shear-thinning behaviour of clays. The yield stress may be a relevant tool to study the workability of soil-cement mixtures.

1. INTRODUCTION

Ground improvement by deep mixing is today a widely accepted method used to improve the permeability, strength and deformation properties of soft soils. The aim of the installation process in deep soil mixing is to inject and spread a binder in dry or slurry form into the soil in order to produce a homogeneous soil-binder mixture. The execution process is very complex compared to other ground improvement methods. The mixing mechanisms that occur during deep mixing are difficult to monitor and present engineering challenges (Larsson, 2003). A large number of factors are known to influence the strength and deformation properties of the treated soils (Terashi, 1997). These factors are mainly related to the characteristics of the binders (type, amount), the soil conditions (soil type, moisture content, and organic content) and the curing conditions. The homogeneity and strength of soils stabilised by deep mixing also largely depend on the mixing conditions and mechanisms that occur during construction (degree of mixing, mixing tool). It has been observed that the mixing of fine grained soils with binders is particularly difficult in extremely cohesive soils of high moisture contents. The mixing mechanisms in deep mixing are directly related to the rheological properties of the materials being mixed. Therefore, rheology is the starting point in understanding the processes involved in deep soil mixing. Knowledge of the rheological characteristics of stabilised soils is very limited (Larsson, 2005).

In current practice, certain simple tests are performed on site to rank and compare flow properties of grouts, concrete and soil-binder mixtures using empirical parameters (Marsh cone, Abrams cone ...). These tests can be very useful in the field for rapid assessments of rheological characteristics but are limited to comparisons of the effects of different dosages on flow properties. They do not allow a quantitative assessment of rheological parameters or the understanding of fundamental physical and chemical interactions between the different constituents in the mixtures.

The use of rheometry allows a more quantitative study of the impacts of the addition of binders on the flow properties of soils. The type of soil and its rheological behaviour have a considerable impact on the efficiency of the mixing process. For coarse grained soils, classic shear geometries cannot be used and only a few rheometers exist that allow the determination of yield stress and viscosity.

The aim of this research is to study the effects of the addition of cement on the rheological characteristics of kaolin clay. In the present investigation, we focus on rheometrical measurements carried out with both

the parallel plates geometry and the ball measuring system (BMS). The objectives are (1) to validate the use of the BMS to measure the rheological parameters of soil-cement mixtures for subsequent studies on coarse grained soils and (2) to examine the effects of the rheological properties on the resulting solidified materials and the reactivity between soils, water and soil mixing conditions.

2. RHEOLOGY OF CLAYS AND CEMENT PASTES

Many authors (Coussot & Ancy, 1999; Lagaly, 1989; Roussel, 2005) have reported that cement slurries and clay-water suspensions could be described in the liquid state as shear-thinning yield stress fluids (Figure 1). The viscosity of shear-thinning fluids decreases as the shear rate increases.

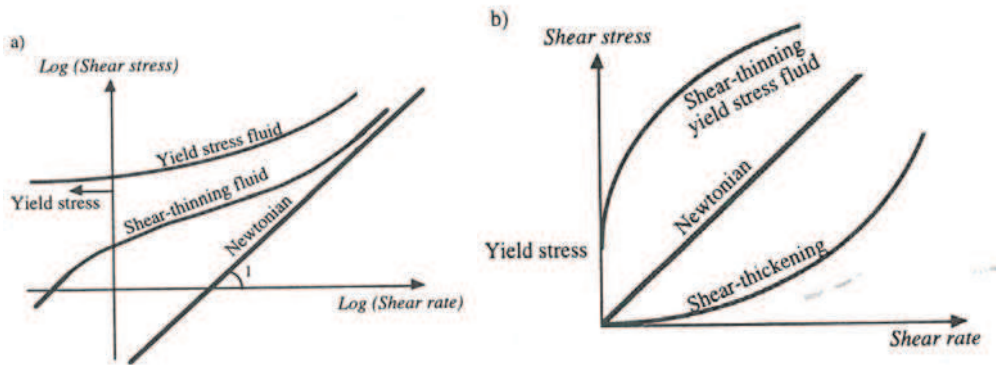


Figure 1: Main steady state behaviour types a) logarithmic diagram b) linear diagram (Coussot, 1997).

The simplest theoretical model for yield stress fluids is the Bingham model (equation 2).

$$\tau = \tau_0 + \eta \dot{\gamma} \quad (1)$$

Where τ_0 = yield stress (Pa), η = viscosity (Pa.s).

It is possible to fit this model to experimental data in a narrow range of large shear rates. However, key material properties may be disregarded by using this model. Consequently, it was proposed to fit a Herschel-Bulkley model (1926) to experimental data:

$$\tau = \tau_0 + K \dot{\gamma}^n \quad (2)$$

Where, K and n = experimental parameters; ($n < 1$ for shear thinning fluids).

Usually, the yield stress represents the strength resulting from the interparticle interaction forces under shear displacement. It corresponds to a critical value of shear stress below which it is not possible to have flow. However, the concept of yield stress is still widely discussed (Tattersal & Banfill, 1983, Barnes & Walters, 1995; Coussot et al, 1996; Barnes, 1999). Indeed, depending on the test procedure, many different values of yield stress can be defined. Even during a single test, different yield stresses can be measured or calculated. This is especially the case for fluids that exhibit a minimum in flow curves. This phenomenon is related to flocculation and deflocculation processes that depend on the hydration of the particles (clay and cement particles are particularly reactive in terms of swelling, phase modification and crystallisation).

3. MATERIALS AND METHODS

3.1. Characteristics of kaolin and binder

The clay used in this study is Speswhite kaolin. This kaolin has a liquid limit WL of 55% and a plasticity index PI of 25%. The cement used is a Portland slag cement containing 85 % ground granulated blast furnace slag (European classification: CEM III/C 32,5 N CE PM-ES NF "HRC") (CEN, 2005). This cement presents a slow strength development, and its initial setting time is 4 hours after hydration. The grain size distributions of the Speswhite kaolin and the cement are presented in Figure 2.

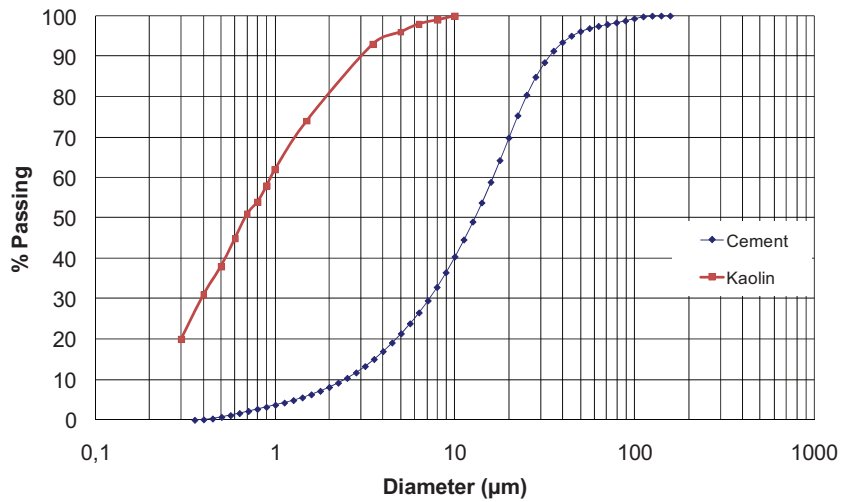


Figure 2: Grain size distributions of Speswhite kaolin and CEMIII cement.

3.2. Sample preparation

For the preparation of the clay samples, the appropriate amount of tap water to reach the target water content was added to the dry soil. Dry cement was then added to the humidified clay and mixed with a laboratory mixer for 5 to 10 minutes at a rotation speed of 2000 rpm. It is well known that the order in which the different constituents are added may have a significant effect on the properties of the mixture. The time between sample preparation and testing was less than 15 minutes. For the cement slurries, dry cement was mixed with tap water for 10 minutes also at a speed of 2000 rpm.

3.3. Testing apparatus and procedure

The tests were carried out using a MCR 501 rheometer manufactured by Anton Paar equipped with parallel plates and the ball measuring system.

The parallel plates geometry consists of two coaxial disks. The material placed between the disks is sheared by their relative rotation. The parallel plates used in this study were of 50 mm in diameter. The gap between the plates was 1 mm.

The ball measuring system consists of a 12 mm diameter sphere that is dragged through a sample volume of approximately 0.5 L (Figure 3) implemented in a standard rheometer (Schatzmann et al, 2009). The rotating speed was controlled and torque measurements were recorded by a computer. The shear stress and the shear rate were then calculated.



Figure 3: The BMS of Müller et al (1999) implemented in a standard rheometer (Schatzmann et al, 2009).

It is well known that clay-water suspensions are thixotropic materials (Coussot, 1997). To obtain consistent and reproducible measurements, specific rheometric procedures must be executed. The procedure used is similar to the method described by Pantet & Monnet (2007). In order to define a structural reference state, measurements with the parallel plate geometry started with an initial shearing

phase (constant shearing at a rate of 300 s^{-1} during 60 s), followed by a rest period of 120 s. Then, the material was subjected to increasing and decreasing shear rates. The difference between the increasing and decreasing values gives indications about the thixotropic properties (i.e. structural evolution) of the fluid. Flow curves were established for shear rates between 0.01 and 300 s^{-1} with the parallel plates geometry and between 0.01 and 50 s^{-1} with the ball measuring system.

3.4. Experimental program

The experimental program is presented in Tables 1 and 2. Kaolin was tested at 3 different moisture contents. Flow curves of cement slurries were established for 5 different water-cement ratios. In total, 7 kaolin-cement mixes were tested. The cement contents C (weight of dry cement/weight of dry clay) varied between 5 and 20% (0.05 and 0.2) and the moisture contents between 0.43 and 1.74. To study the effects of an increase in cement content, 4 kaolin-cement mixtures were prepared with a water/clay ratio equal to 1 and with increasing cement/clay ratios between 0.05 and 0.20 (mixes n°1 to 4, Table 2). The 3 other kaolin-cement mixes were prepared with a cement/clay ratio of 0.15 and different water/clay ratios.

Table 1: Characteristics of the kaolin and cement suspensions

Soil	Moisture content (kaolin) / Water-cement ration (cement slurries)				
	w = weight of water/weight of dry solids				
Kaolin	2.00	1.50	1.00	-	-
Cement	0.60	0.55	0.50	0.45	0.42

Table 2: Characteristics of the kaolin-cement mixes

Mix n°	C= weight of dry cement/weight of dry clay	W= weight of water/weight of dry solids	weight of water/weight of dry clay
1	0.05	0.95	1.00
2	0.10	0.91	1.00
3	0.15	0.87	1.00
4	0.20	0.83	1.00
5	0.15	1.74	2.00
6	0.15	1.30	1.50
7	0.15	0.43	0.50

4. EXPERIMENTAL RESULTS AND ANALYSES

4.1. Flow curves of kaolin

The flow curves obtained using the parallel plates and the ball measuring system for Speswhite kaolin at different moisture contents are presented in Figure 4. For both geometries, the shear stresses measured increase as the moisture content decreases. This can be explained by the increasing interaction between the clay particles as their concentration increases.

The yields stresses obtained for the two geometries, taken as the shear stress at a shear rate of 1 s^{-1} , are compared in Table 3. An acceptable agreement is found between the yield stresses obtained using the parallel plates and the ball measuring system.

No thixotropic effects were observed for the Speswhite kaolin. Thixotropic behaviour exhibited by other clay minerals such as smectites is related to high reactivities and modifications in particle size and surface properties caused by the hydration process (Lagaly, 1989; Besq et al., 2003; Pantet & Monnet 2007).

Table 3: Yield stresses of kaolin at different moisture contents

Geometry	Yield stress (Pa)		
	W=1.0	W=1.5	W=2.0
Parallel plates (average)	300	55	7.5
Ball Measuring system	300	43	14

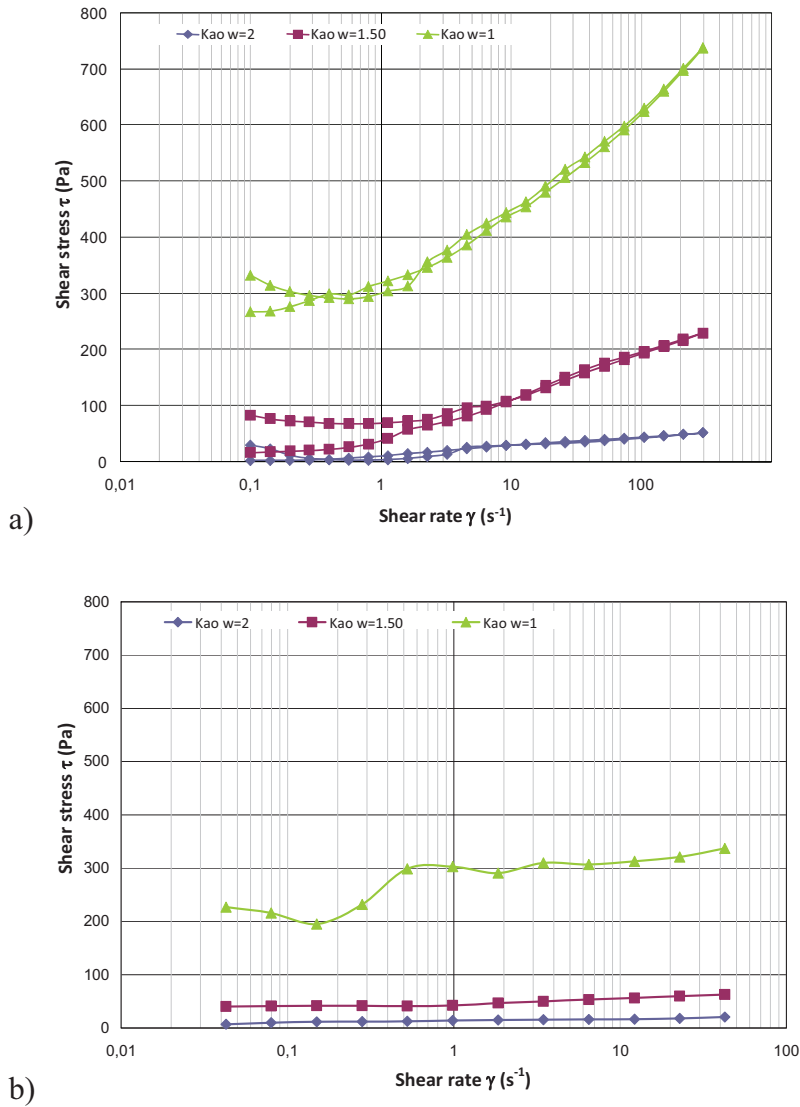


Figure 4: Flow curves for Kaolin using a) the parallel plates b) the ball measuring system.

4.2. Flow curves of cement slurries

The flow curves obtained using the ball measuring system for cement slurries with different concentrations are plotted in Figure 5. The yield stresses, taken as the shear stress at a shear rate of 1 s^{-1} , are given in Table 4.

Table 4: Yield stresses of cement slurries at different concentrations

Geometry	Yield stress (Pa)				
	W=0.6	W=0.55	W=0.50	W=0.45	W=0.42
Ball Measuring system	17	50	153	415	830

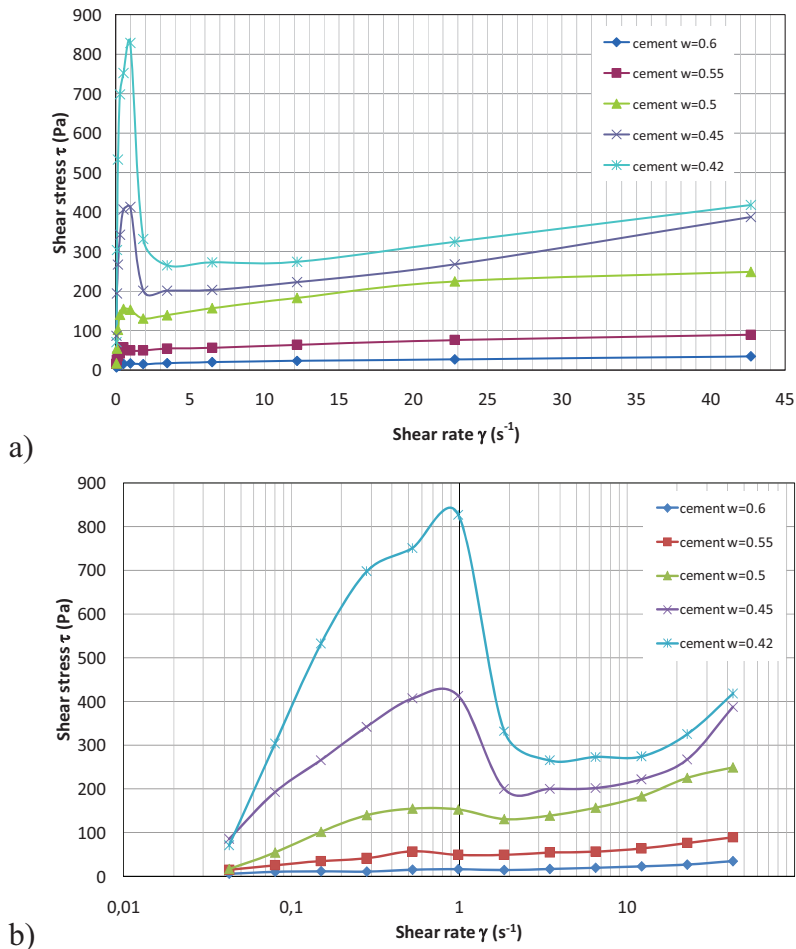


Figure 5: Flow curves for cement slurries a) linear scale b) logarithmic scale.

The measured flow curves are above the equilibrium state flow curves. These results demonstrate that the deflocculation process was insufficient to bring the structure to its equilibrium state. This type of flow curve is directly related to the duration of the experimental measuring cycle as reported by Roussel (2005, Figure 6).

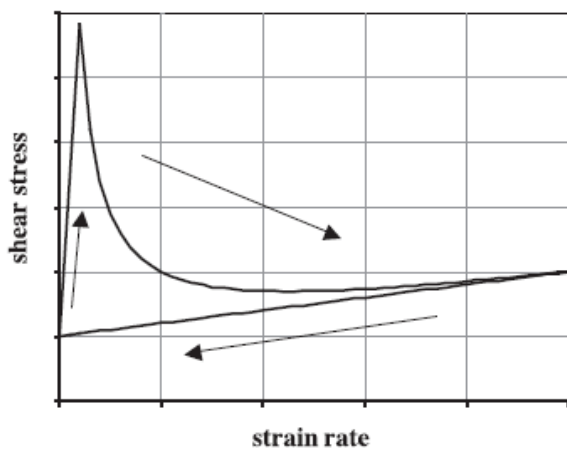


Figure 6: Cement paste flow curve: short cycle test; steady state not reached (Roussel, 2005).

4.3. Flow curves of clay-cement mixes

The flow curves obtained for clay-cement mixtures using the ball measuring system are plotted in Figures 7 and 8. The flow curves are similar to those obtained for the cement slurries. The behaviour, once the minimum is reached, is rheopetic and can be related to the hydration process. Figure 7 shows that the

addition of dry cement affects the measured shear stresses inasmuch as it causes an increase in particle concentration. The effect of moisture content on the rheological behaviour of cement-kaolin mixes is clearly visible in Figure 8 as the measured shear stresses drastically increase for moisture contents lower than 100%. The yield stresses (shear stress at a shear rate of 1 s^{-1}) are summarized in Table 5.

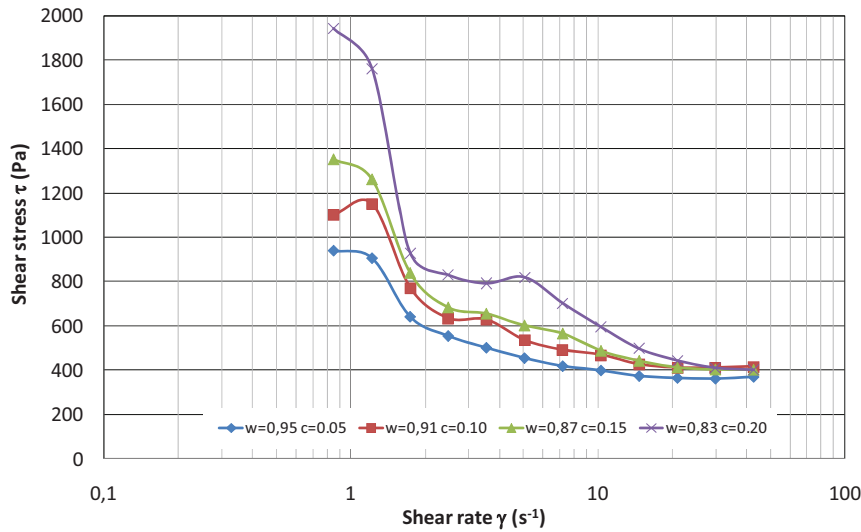


Figure 7: Flow curves for clay-cement mixes n°1 to 4 using the BMS (constant water / clay ratio; different cement contents).

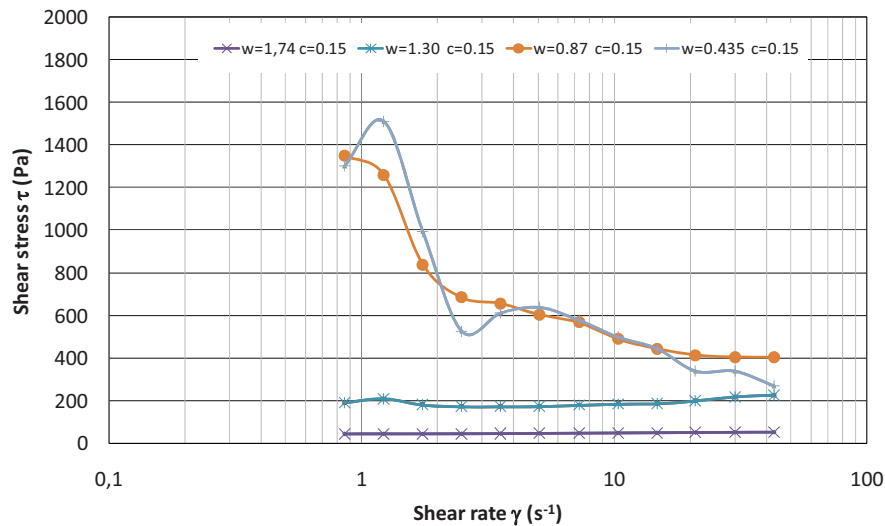


Figure 8: Flow curves for clay-cement mixes n°3 and n°5 to 7 using the BMS (constant cement content; different water / dry solid ratios).

Table 5: Yield stresses of kaolin-cement mixes measured with the BMS

Mix n°	1	2	3	4	5	6	7
C= weight of dry cement/weight of dry clay	0.05	0.10	0.15	0.20	0.15	0.15	0.15
W= weight of water/weight of dry solids	0.95	0.91	0.87	0.83	1.74	1.30	0.435
Yield stress (Pa)	906	1150	1260	1760	45	210	1510

5. DISCUSSION

The results presented above can be related to observations made in the field regarding the installation process of deep soil mixing elements. Many others have reported that faster tool rotation speeds increase

the homogeneity and strength of treated soils (CDIT, 2002). In the case of fine grained soils, this can be explained by the shear-thinning behaviour of clays (i.e. lower viscosity at higher shear rates). As the blade rotation speed increases, the soil is subjected to increasing shear rates. Assuming that homogenising low viscosity fluids or suspensions is easier than mixing viscous fluids, the efficiency of the mixing process is improved at higher shear rates (blade rotation speeds). The clay-binder mixture produced is more homogeneous and therefore of higher strength after curing.

The effects of yield stress on the mixing process in deep mixing are less straightforward as the stresses produced by the rotation of the mixing tool are much higher than the yield stresses of clay suspensions. The yield stress may be related to the workability of soil-cement mixtures. In general, no compaction is performed during the installation of soil mixing columns. The soil-cement mixtures must therefore be sufficiently fluid to be self-compacting. This implies that the mixes should have a yield stress which is low enough to allow the mixture to flow under its own weight and fill the voids created by the passing of the mixing tool. The results obtained on kaolin-cement mixtures clearly show the predominant effect of moisture content on yield stress (Figure 9). Further research and experiments are needed in this direction as it may be possible to determine, for a particular soil-cement mixture, an optimum moisture content which does not significantly alter the strength of the treated soil after curing but at which the yield stress in the fresh state is sufficiently low for the mixture to be self-compacting. Further field experiments could allow the determination of yield stress thresholds for the workability of soil-cement mixtures.

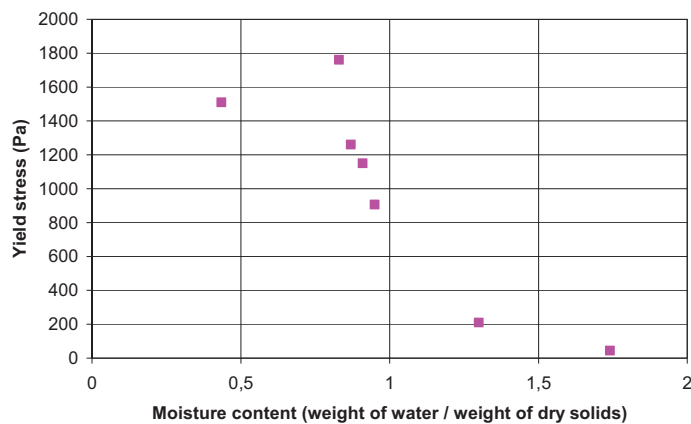


Figure 9: Yield stress versus moisture content for kaolin-cement mixes.

6. CONCLUSION

In this paper, the flow properties of kaolin, cement slurries and kaolin-cement mixtures at various moisture contents were measured using a rheometer with two different geometries: the parallel plates and the ball measuring system. For all mixtures tested, the yield stresses decreased as the moisture content increased. A good agreement was found between the stresses measured using the parallel plates and the ball measuring system for kaolin suspensions, validating the use of this shear geometry for subsequent studies on coarse grained soils. The results are discussed with respect to in situ soil mixing processes. It is proposed that observations made in the field on the relation between blade rotation speed and strength and homogeneity of treated soils can be explained by the shear-thinning of clays. The yield stress seems to be a relevant tool to study the workability of soil-cement mixtures.

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