Residual strength of kaolin and bentonite: the influence of their constituent pore fluid

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The residual strength of clays is affected by their mineral composition and by the nature of their constituent pore fluid. In principle, both factors may influence either strength parameters or stresses, but it is not yet completely clear how this influence works. Previous publications have elucidated some aspects of clay residual strength behaviour. This Paper investigates further the roles of minerals and pore fluid composition on the residual strength of clayey soils. It describes and analyses tests on kaolin, bentonite and their mixtures exposed to distilled water and sodium chloride solutions with given concentrations. The results show that the shear strength of kaolin is not affected by the solutions used, whereas the residual strength of bentonite varies greatly because of the inward salt diffusion towards the clay. Further, for the clay mixtures with any of the pore fluids considered, the weaker component has the greater influence on the behaviour of the mixture.

KEYWORDS: chemical properties; clays; microscopy; mineralogy; shear strength.

INTRODUCTION
The residual strength of soils plays a very important role in soil mechanics. It is the only available strength for slopes that have experienced previous movements and that have pre-existing shear surfaces, and the drop of strength from peak to residual can provide a measure of the risk of progressive failure of slopes. Besides its practical importance, an analysis of residual strength is very important for the elucidation of the shearing mechanism. Since it is independent of loading history and initial structure, residual strength is a unique feature of the soil-pore fluid system. This allows an easier analysis of the parameters that may influence the shear behaviour of soils.

The first studies on this subject tried to correlate residual strength with easily measurable parameters such as clay fraction (CF) and plasticity index $I_p$. Some results for natural soils and artificial mixtures are shown in Fig. 1, where $\phi'_r$ is plotted against CF. Experience has shown that for $CF < 20\% - 25\%$, $\phi'_r$ is close to the friction angle of the critical state and is usually greater than $20^\circ$ (Skempton, 1985); for $25\% < CF < 50\%$ results are extremely scattered. For $CF > 50\%$, the residual strength of soil is equal to the residual strength of its clayey part, and the values it may take vary greatly with the type of clay, becoming very low in some cases. The lowest values are exhibited by clays formed by platey particles (Kenney, 1967; Chattopadhyay, 1972), where one finds a significant drop from critical state strength to residual strength which is attributed to the reorientation of platey particles that occurs through the shearing process (Morgenstern & Tchalenko, 1967; Lupini,
Skinner & Vaughan, 1981; Skempton, 1985). Moreover, clays with platey particles of different mineral compositions exhibit differences in residual strength (e.g. Kenney, 1967). In addition, the residual shear strength values of some clays depend on pore fluid composition (Kenney, 1967; Balasubramonian, 1972; Sridaharan & Ventakappa Rao, 1979; Chattopadhyay, 1972; Chatterji & Morgenstern, 1989; Moore, 1991).

In principle, the fluid composition may influence the thickness of the double layer (Lambe, 1960), the type and size of the elementary aggregates (van Olphen, 1956; Bennett & Hulbert, 1986; Stawinski, Wierzchos & Garcia-Gonzalez, 1990; Chen, Cushman & Low, 1990) and the interparticle forces. Of these factors, the last is believed to be the most important with regard to the residual shear strength of some clays (Chattopadhyay, 1972; Sridaharan & Ventakappa Rao, 1979; Chatterji & Morgenstern, 1989). The type and size of particle aggregates seem to play an important role in the rheological behaviour of sodium-montmorillonite suspensions (Chen et al., 1990), but their influence on the shear strength of clayey soils has not been sufficiently investigated.

In summary, the main parameters of the soil-pore fluid system that should affect the residual shear strength of clays are the shape and size of particles, pore fluid composition and the nature of lattice cations. Since the influence of shape has already been sufficiently investigated, this Paper analyses the differences in residual shear strength between clays whose particles have similar shape. To this end, two clays with different sizes but almost the same platey particle shape have been chosen, i.e. kaolinite and montmorillonite. They have been tested alone and in mixtures, in distilled water and in salt solutions, and their shear surfaces have been observed by scanning electron microscopy (SEM).

### CLAYS TESTED AND EXPERIMENTAL PROGRAMME

The tested clays were commercial kaolin and bentonite, provided by Igma srl (Sassuolo, Italy), and their mixtures. The materials were found to have 100% CF. Their mineralogical composition was determined by means of X-ray powder diffraction (XRD). These measurements were conducted by use of a Philips apparatus with CuKα radiation. This analysis showed that the bentonite sample was composed of sodium-montmorillonite (88%-90%) with a good degree of crystallinity, dolomite (8%-10%), kaolinite (<5%), and quartz and feldspars (<5%). The kaolin sample was composed of kaolinite (78%-80%) with a good degree of crystallinity, quartz and feldspars (10%-12%), illite (8%-10%) and smectite (<5%).

The mixtures of the two clays were made on the basis of dry weights. Index properties of materials and their mixtures are given in Table 1. Remoulded samples were produced by mixing the powdered clays with distilled water to a slurry at about its liquid limit. The samples were consolidated in stages up to an axial stress about 500 kPa, then they were cut horizontally and sheared. Afterwards, the loads were progressively reduced and each sample was sheared at several axial stresses between 500 kPa and 200 kPa. The 100% kaolin sample was the only one tested to an axial stress of 20 kPa.

The residual shear strength was determined by use of Casagrande direct shear boxes. In order to obtain large shear movements, samples were sheared back and forth until the minimum strength was obtained and maintained for at least three or four cycles of shearing. A rate of dis-
placement of 0.005 mm/min was adopted; about 24 h elapsed between the end of a cycle and the beginning of the next one. The temperature was kept at about 20°C.

Once the residual strength was reached, distilled water was replaced in the external box by 1M NaCl solution which was continuously renewed. This produced changes in strength. When, under the new conditions imposed by the electrolyte, the samples reached constant values of shear strength, the cell solution was replaced by sodium chloride saturated solution; under these new conditions the shearing of the samples was continued. Some tests were extended by replacing the sodium chloride solution with distilled water: the latter was continuously renewed until a new constant value of strength was reached. Some shear tests were performed on samples obtained by mixing powdered clay directly with saturated sodium chloride solution. Since the addition of salt to the cell solution seemed to produce further and significant settlements in the samples containing bentonite, some oedometer tests were carried out. Each test began in distilled water which, when the clay had consolidated under a fixed confining stress, was replaced by sodium chloride saturated solution. The microstructure of the shear planes and of the longitudinal sections containing the shear zone was observed by SEM: the samples were first air-dried, and then fractured in the required direction by scoring round the surface with a razor blade and manually snapping the sample, as described by Sides & Barden (1971). The surfaces were not coated with any metal. The microscope used was a Cambridge Stereoscan 250 MKII.

RESULTS

The results obtained in tests performed on 14 specimens of kaolin–bentonite mixtures are presented in Table 2 and Figs 2–9.

Tests in distilled water

The results of tests performed using distilled water as both pore fluid and cell solution are plotted in the form of residual shear strength against applied axial stresses in Fig. 2. Since it has been observed (Kenney, 1967; Chattopadhyay, 1972) that the residual strength of kaolin and bentonite is independent of axial stress above 200 kPa, but can depend strongly on axial stress for lower values, all samples were tested for \( \sigma'_a > 200 \) kPa (apart from one case). The results of Kenney and Chattopadhyay are confirmed by those shown in Figs 2 and 3. For the kaolin sample tested for axial stresses \( \sigma'_a < 200 \) kPa, it was found that the variation of \( \tau'_r \) with stress level is clearly non-linear, whereas for \( \sigma'_a > 200 \) kPa and for any mixture, the representative points lie close to straight lines passing through the origin. For \( \sigma'_a > 200 \) kPa, the cohesion intercept is null and it is thus possible to read the results in terms of residual friction angle \( \phi'_r \): a \( \phi'_r \) value of about 10° was obtained for kaolin and of about 4° for bentonite, except for one sample of bentonite which gave a value of about 6°. These values correspond well with those reported for the same clays by other authors (Morgenstern & Tchalenko, 1967; Kenney, 1967; Morgan, 1967; Cullen & Donald, 1971; Chattopadhyay, 1972; Chatterji & Morgenstern, 1989).

In Fig. 4 the values for \( \tau'_r/\sigma'_a \) in the case of the two-mineral mixtures are plotted against the percentage (dry weight) of bentonite. As this percentage increases, the residual friction angle of the mixtures decreases: a content of about 50% reduces it to values equal to those obtained in the case of bentonite.
Tests in sodium chloride solutions

When the residual shear strength was reached during standard tests in distilled water, the cell fluid was replaced by sodium chloride solutions. The resulting effects are seen in Fig. 5, which shows the shear trends of kaolin and bentonite as examples. The replacement of the cell solution is shown by vertical arrows. Both tests were conducted in distilled water until a constant value of strength was reached. Distilled water was then replaced by 1 molar sodium chloride solution. Fig. 5 shows that the addition of salt influences neither the residual shear strength nor the settlements of kaolin, but it causes a significant change in the behaviour of bentonite: its residual friction angle, which is about 6° in the case of distilled water, increases to a value of 9°.

Table 2. Test results for kaolin, bentonite and kaolin-bentonite mixtures

<table>
<thead>
<tr>
<th>Test</th>
<th>Bentonite content: %</th>
<th>$\sigma'_b$: kPa</th>
<th>$\tau'_b/\sigma'_b$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Distilled water</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>516 320 221</td>
<td>0.18 0.18 0.19</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>516 320 271</td>
<td>0.17 0.17 0.18</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>422</td>
<td>0.17</td>
</tr>
<tr>
<td>4</td>
<td>0</td>
<td>418 210 98 49 20</td>
<td>0.18 0.20 0.27 0.30 0.35</td>
</tr>
<tr>
<td>5</td>
<td>25</td>
<td>516 369 221</td>
<td>0.12 0.12 0.12</td>
</tr>
<tr>
<td>6</td>
<td>25</td>
<td>451</td>
<td>0.07</td>
</tr>
<tr>
<td>7</td>
<td>50</td>
<td>221</td>
<td>0.07</td>
</tr>
<tr>
<td>8</td>
<td>50</td>
<td>456</td>
<td>0.07</td>
</tr>
<tr>
<td>9</td>
<td>60</td>
<td>454</td>
<td>0.07</td>
</tr>
<tr>
<td>10</td>
<td>75</td>
<td>516 369 221</td>
<td>0.07 0.07 0.07</td>
</tr>
<tr>
<td>11</td>
<td>75</td>
<td>471</td>
<td>0.05</td>
</tr>
<tr>
<td>12</td>
<td>100</td>
<td>418 320 221</td>
<td>0.07 0.06 0.06</td>
</tr>
<tr>
<td>14</td>
<td>100</td>
<td>415</td>
<td>0.07</td>
</tr>
<tr>
<td>15</td>
<td>100</td>
<td>415</td>
<td>0.11</td>
</tr>
</tbody>
</table>
Again, the substitution with saturated solution does not affect kaolin, but causes major changes in the behaviour of bentonite, whose residual friction angle increases to about 18°. When the sodium chloride saturated solution is replaced by distilled water, \( \phi_r' \) returns to the values previously obtained in distilled water. During this stage, the sample was cut manually again, since this process ensured the flatness of the shear surface, just as at the beginning of the test. So, for the bentonite, the presence of salt leads to a surprising increase in shear strength (by means of an almost completely reversible process, unfortunately). As noted subsequently, this reversibility cannot be generalized, but is influenced by the kind of bentonite used and the pore solution.

In Fig. 5, the horizontal arrows indicate the values of residual shear strength obtained by mixing powdered bentonite and kaolin directly with a saturated NaCl solution. Fig. 5 shows that these values are equal to those obtained by the addition of salt to the cell fluid. In Fig. 6, the \( \tau'_r/\sigma'_s \) values are plotted against the percentage of bentonite for all tests: in distilled water, 1 molar sodium chloride solution and saturated sodium chloride solution. All the samples tested in 1 molar sodium chloride solution reached a strength higher than that exhibited in distilled water and very close to that of kaolin. The replacement of 1 molar by saturated sodium chloride solution gave additional strength to the specimens, and the curve interpolating the experimental points has a specular shape compared to the curve representing tests in distilled water. Under the new conditions determined by the latter substitution, the bentonite samples exhibit the highest values of strength, while 50% in dry weight of kaolin suffices to reduce the strength of the mixtures to values equal to the kaolin values.

Fig. 7. Void ratio plotted against effective stress for three specimens of bentonite: oedometer test data

For bentonite settlements, Fig. 5 shows that the addition of 1M solution causes an increase in settlement which tends to vanish as shearing proceeds. The addition of saturated solution causes higher settlement, whereas the replacement with distilled water causes a tendency to swelling. To demonstrate that these settlements are due to phenomena related to the addition of salt rather than to shear, oedometer tests were performed on three bentonite specimens which were consolidated to fixed confining stresses, after which they were exposed to a sodium chloride saturated solution and then reloaded. The specimens tested were 2 cm thick. The addition of the salt produced noticeable volume change, as shown in Fig. 7 in terms of void ratio against effective stress. Further, the time-compression curves due to the addition of salt shown in Fig. 8 indicate that the consolidation was rather rapid, just as observed during the shear tests (Fig. 5).
To investigate further the effects of differing concentrations of salt solution on the geotechnical parameters, the values of $I_p$ obtained by the standard technique were compared to those obtained by mixing the powdered mixtures with 1M sodium chloride solution and sodium chloride saturated solution. In Fig. 9 these values are plotted against the percentage of bentonite (dry weight) for the mixtures considered. It is seen that $I_p$ decreases dramatically in the transition from distilled water to 1M and to saturated solution.

**Scanning electron microscopy**

The first, defeasible, analysis of the results obtained in distilled water is that bentonite shows a lower strength than kaolin for purely mechanical reasons: this interpretation would justify the difference in strength in terms of a possible difference in roughness of shear surfaces caused by the different sizes of particles or particle aggregates. To test this interpretation, scanning electron micrographs of shear surfaces were made.

Figure 10 shows the microstructure of the shear surface (from a perspective normal to the surface) for three samples tested in distilled water. Fig. 11 shows micrographs of longitudinal sections through failure surfaces of the same samples. The kaolin shear surface looks almost rough, while the surface of the bentonite sample looks as though it is composed of thin and very smooth tablets, strongly oriented in the direction of shear. The shear surface of the 25% bentonite sample looks more similar to the bentonite surface than to the kaolin surface: a thin layer of bentonite seems to cover the kaolin, and the latter can be seen only at random spots.

Figure 12 shows, as an example, the case of a 100% bentonite sample tested in NaCl saturated solution. Since scanning is possible only on dried samples, the diffuse presence of salt precipitate produced by drying makes it difficult to observe

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**Fig. 9. Influence of fluid composition on $I_p$**

**Fig. 10. Scanning electron micrographs showing the shear surfaces of: (a) a kaolin sample; (b) a bentonite sample; (c) a 25% bentonite sample, tested in distilled water (the surfaces are viewed from a perspective normal to them)**
the shear surface of samples tested in sodium chloride solutions directly. However, the structure of the sample examined (Fig. 12) can be distinguished on some parts of the shear surface, where it looks quite similar to the structure observed in absence of salt. None the less, the residual shear strengths of the two bentonite samples under consideration (Figs 10(c) and 12) differ greatly, hence some other parameter probably exists whose influence on the residual shear strength of clays is greater than that of shear surface roughness.

**DISCUSSION OF RESULTS**

In order to evaluate the results, it is necessary to understand the phenomena that occur when a specimen of clay obtained by mixing powder with distilled water is exposed to a salt solution. Two phenomena can occur simultaneously: inward diffusion of salt towards the clay, due to different salt concentrations, and outward flow of fluid, due to osmotic gradients (Barbour & Fredlund, 1989). Both processes produce volume changes, which are clearly visible in Figs 5(a), 7 and 8 for the case of bentonite. To determine which of the two is the prevailing phenomenon, Barbour & Fredlund (1989) compared the results of laboratory tests on deformability of two clay soils (highly plastic Regina clay and sand–Na montmorillonite mixture) exposed to 4M sodium chloride solution with the results of a numerical simulation of the two processes that cause a change in volume. For the clays they tested, the predominant process was the diffusion of salt.

The results for bentonite exposed to salt solution and bentonite mixed with salt solution are the same (Fig. 5(a)), suggesting that the increase
in residual shear strength produced by the addition of salt to the cell solution is caused by the inward diffusion of the salt towards the clay (i.e. by a direct action of salt on clay particles) rather than by the osmotic outward flow. The direct action on clay particles results in a change in the physico-chemical forces of interaction. Variations in the balance of these forces cause significant changes in the type of aggregate (edge-face, edge-edge, face-face) and in mean aggregate radius (e.g. van Olphen, 1956; Bennett & Hulbert, 1986; Chen et al., 1990; Stawinski et al., 1990). Stawinski et al. showed that the microstructure of bentonite formed in a water suspension is dominated by an edge-face type of aggregation. The addition of sodium chloride beyond a given concentration (lower than the concentrations considered in this Paper) leads to the formation of 'very compact irregular aggregates having a multi-layer structure of the face to face type'. They also found that the mean radius of the aggregates increases beyond that salt concentration.

The variation of \( I_p \) with salt concentration (Fig. 9) can be seen as further evidence in favour of this interpretation; previous results could be interpreted as showing a change in the value of the aggregates' specific surface and, consequently, a change in \( I_p \). This would suggest the occurrence of changes in the shear behaviour of clay soils, if such behaviour is assumed to be determined by particle aggregates. However, this is merely conjecture, as there is no evidence for the existence of aggregates on the shear surface. The scanning electron micrographs (Figs 10–12), although they allow a qualitative evaluation of the shear roughness, do not reveal the type of particle aggregates.

At the moment, the behaviour of clays is interpreted on the basis of simplified models of individual particle interaction by most researchers, including Chatterji & Morgenstern (1989), who analysed a series of tests on an Na-montmorillonite percolated with a 35 g/l solution of sodium chloride and with a final pore fluid of 33-6 g/l solution, before and after leaching with distilled water. At first, by presupposing a classical interpretation of their results, they found a value of \( \phi_s = 10^\circ \) before leaching and \( \phi_s = 3^\circ \) after leaching (these values compare favourably with the results in the present Paper for the case of 1 molar sodium chloride solution and of distilled water respectively). However, they did not endorse the classical interpretation and they held that the strength improvement obtained by using an electrolyte as pore fluid must be interpreted in terms of the 'modified effective stress law for active clay water systems', which takes account of the 'physico-chemical forces of interaction arising out of a net charge deficiency in the lattice structure, a high specific surface and the chemical environment' (Chatterji & Morgenstern, 1989). According to this new interpretation, the strength improvement originates from an increase in the true effective normal stress rather than from an increase in friction angle (whose true value should also be \( \phi_r' = 10^\circ \) after leaching).

The same hypotheses are proposed by Sridharan & Ventakappa Rao (1979), who sheared kaolin and montmorillonite samples mixed to fluids with differing dielectric constants, in order to produce a change in the physico-chemical forces of interaction. The interpretation offered could explain why the addition of salts to the pore fluid makes the bentonite behaviour vary but does not influence the kaolin behaviour: in fact, in the present case, bentonite has a much greater specific surface than kaolin. An insignificant effect of the pore fluid NaCl content on kaolin was also found by Chattopadhyay (1972), a significant effect was found by Moore (1991), who investigated the shear behaviour of some samples of kaolinite, montmorillonite and two natural clays, treated with NaCl and CaCl\(_2\) solutions with concentrations of 0-2–1-0 g/l. Moore found that a change in concentration from 0-2 g/l to 1-0 g/l resulted in an increase in residual strength for all materials. His results and those of this Paper cannot be compared directly because of the great difference in concentration of the solutions used. The range of concentrations Moore used gives rise to very interesting phenomena of microstructural change, as experiments on sodium-montmorillonite suspensions by Stawinski et al. (1990) and Chen et al. (1990) seem to show.

The reversibility of the process shown for bentonite (Fig. 6) is probably due to the use of sodium chloride solutions for an Na\(^+\) saturated clay, which means that the addition of the salt does not produce any lattice-cation substitution. The lattice-cation substitution could instead explain the partial irreversibility found in other tests on other clays with other salts (which are currently being examined).

A different bentonite from the one examined in this Paper (the two are very similar) was tested in a CaCl\(_2\) saturated solution. The bentonite was sheared first by use of distilled water, second by exposing it to a CaCl\(_2\) saturated solution, and third by exposing it to distilled water again. The ratio \( \tau_c/\sigma_n \) after the third stage (0-18) was greater than that after the first stage (0-11) and lower than that after the second stage (0-27).

CONCLUSIONS

Shear tests on kaolin and bentonite have shown that the behaviour of kaolin is not influenced by exposure to 1M sodium chloride and
saturated sodium chloride solution, but the behavior of bentonite is highly influenced by such exposure. When tests are carried out by use of distilled water, bentonite assumes lower values of residual shear strength than kaolin and the presence of 50% dry weight of bentonite reduces the residual strength of the mixture to values typical of bentonite itself (the lowest values found in clay minerals). However, when the specimens are exposed to a sodium chloride saturated solution, bentonite shows the highest value of residual shear strength, while 50% dry weight of kaolin is sufficient to reduce the values of the mixtures to values close to those of kaolin alone.

The increase of residual shear strength observed for bentonite specimens exposed to sodium chloride solutions is, in this case, almost completely reversible. However, this result cannot be generalized, probably because lattice-cation substitution does not occur when sodium chloride saturated bentonite and sodium chloride saturated solution are used. This substitution could cause a partial irreversibility.

The increase in strength of bentonite and of mixtures can occur because salt becomes diffused in the pores of the clay. When the salt enters the pores it causes the interparticle forces to vary, but this is probably not its only effect. The noticeable variation of \( I_p \) suggests that more complex phenomena probably occur.

The current prevailing opinion is that the strength improvement obtained by use of a sodium chloride solution as pore fluid does not depend on a hypothetical increase in the strength parameter \( \phi'_s \), but only on the increase in true effective interparticle stresses, which vary with pore fluid salt concentration because of the existence of significant physico-chemical forces. This interpretation is supported by the fact that addition of sodium chloride to the pore fluid causes an increase in the strength of bentonite, and of mixtures containing bentonite, which is not accompanied by an observable (by SEM) variation in the structure of particle aggregates on the shear surface.

However, further experimentation and analysis are required before it can be concluded that the physico-chemical forces constitute the main influence, and changes in microstructure have no effect.

REFERENCES


