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# Environmental profile of bentonite drilling fluids for civil engineering applications

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ABSTRACT: Bentonite is the commercial name of a class of materials composed mainly of montmorillonite, which may also contain kaolinite, feldspars, micas, cristobalite and quartz. Such product is widely used for different civil engineering applications such as foundations (piles and diaphragm) and tunnel excavations (TBM, Micro-TBM and other no-dig technologies). This paper presents the results of a Research program developed by ITALFERR and GEEG including an experimental investigation based on the analysis of geotechnical and chemical properties of bentonite-based slurries in order to compare and identify the main properties of fluids prepared either with natural or polymer-modified bentonites. The interaction of the drilling fluids with the environment is an extremely delicate issue that must be carefully addressed during the design and construction phases. This study aimed at acquiring knowledge and defining best practices for the proper management of drilling fluids and the sustainable reuse of soils and rocks during and after the excavation.

## 1 INTRODUCTION

### 1.1 *Civil engineering applications*

Bentonite slurries are widely used since decades in two macro-sectors in the field of civil engineering: the construction of vertical drilling, such as piles and diaphragms walls or deep drilling for gas/oil extraction, and horizontal perforations, such as the excavation of tunnels with TBM, Micro-TBM and other no-dig technologies. During vertical drilling, the use of bentonite suspensions allows hole stabilization by sealing the walls, preventing collapse during excavation operations, and allows the transport of the solid material out of the excavation. In tunneling and microtunnelling, bentonite slurry has a dual role: on one hand, it is used to stabilize the excavation walls and transport resulting materials outside before laying the final coverage, as in the case of piles and diaphragms; on the other hand, it acts as lubricant avoiding or reducing consumption on excavation tools. Therefore, a drilling fluid, in general, must perform several functions: i) Borehole support and stabilization; ii) Debris transport to the surface; iii) Friction reduction between the excavation tools and the borehole walls; iv) Excavation tools cooling and cleaning.

Bentonite fluids are obtained by adding to the water a few percentage units by weight of bentonite (usually between 4.5% and 9%), mixing the solution and leaving it to rest to ensure the dispersion and hydration of the particles.

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Bentonite is a clay essentially based on montmorillonite (over than 80%) and secondary minerals as quartz, calcite and micas (Besqa et al., 2003) used for the preparation of drilling water-based fluids thanks to the adsorption of water and, as a consequence, the swell up of its volume (Jock Asanja et al., 2019) according to well-known mechanisms (Zou et al., 2022). The attractive and repulsive forces between clay particles (Coulombic and van der Waals) are responsible for the rheological behavior of the fluid (Alemdar et al., 2005). Bentonite fluids exhibit a non-Newtonian and thixotropic behavior. When a shear stress is applied the material transitions from a three-dimensional high-viscosity gel network to a fluid state because of the orientation of the mineral particles in the stress direction and the break of the gel structure; such gel network is restored when shearing is removed (Klessidis, 2008). Only in the case of very low concentrations such suspensions exhibit Newtonian and pseudoplastic behavior (Power law) (Huang et al., 2016).

Natural bentonites include sodium or calcium montmorillonite that differ in terms of hydraulic conductivity when adopted in water fluids mud (Barats et al., 2017); other commercial bentonite formulations are available including additives (electrolytes, surfactants and polymers) to induce changes on the interfacial region between clay particles for the modification of the clay dispersion in water and its rheological behavior (Alemdar et al., 2005). Among polymers starch (Dias et al., 2015), guar gum (Anderson, 1974), xanthan gum (Navarrete, 2000) and cellulose-based materials (Iscan et al., 2007) are example of natural polymers, while as synthetic ones, polyacrylamide and polyacrylates (Yan et al., 2013; Nunes et al., 2014; Binqiang et al., 2021) were tested.

Although the effect of the additives is well exploited in literature, poor information on environmental impact of polymer modified bentonites are available. To this purpose, the aim of this work is to provide a detailed characterization in term of geotechnical and chemical properties of bentonite (natural and polymer-modified) to assess a systematic approach for the evaluation of the possible impact of bentonite residue on excavated soils coming from drilling operations.

#### 1.1.1 *Borehole stabilization and support*

The thixotropic properties of bentonite slurry allow to stabilize the excavation in order to perform the concrete casting through the formation of a millimeter-thick film called “cake”, “mudcake” or “filtercake”, on the hole walls. Because of filter cake low permeability, an effective stabilizing pressure is applied to the borehole surface, which is equal to the difference between the pressure of the slurry inside the borehole and the interstitial pressure of the soil water.

#### 1.1.2 *Transport and separation of soils debris*

Beside supporting the excavation walls, bentonite slurry is also used to transport excavated soil to the surface and outside the borehole. During excavation works, bentonite slurry density plays a decisive role by keeping the spoil in suspension. Stability properties also become important, which is the ability of the bentonite to remain homogeneously dispersed in the water avoiding separation or sedimentation phenomena. The sludge circulation system conveys the drilling fluid containing the suspended excavation debris to a separation plant; this mechanical process led to the separation of coarse particles (debris), fluid (water) and fine particles (bentonite) by the use of screening machines, a centrifuge, a filter press system, or simple settling tanks equipped with hydrocyclones. By the separation it is possible to recover the solid spoil deprived of most part of the bentonite sludge and recirculate the bentonite fluid in the drilling process.

#### 1.1.3 *Lubrication and friction reduction*

In underground works construction (hydraulic, railway or road tunnels), where trenchless technologies such as microtunnelling, pipe pushers or Tunnel Boring Machines are exploited, bentonite or polymers also allows the lubrication of the equipment. In fact, lubricating action is needed due to the size of the excavation face and due to the extent of friction between the excavation tools and the soil/rock.

### 1.1.4 *The use of bentonite in the construction of piles and diaphragms walls*

In piles and diaphragms walls realization, the amount of bentonite is contained in the filtercake inside the borehole. Thickness of the filtercake layer depends on the soil grain size and varies in a range of a few millimeters. The tightness of the filtercake limits the interaction between bentonite and surrounding environment during the drilling activities. Environmental impacts of bentonite usage could only be related to interaction with the crossed lithologies, to the following phases of reuse of the excavated soil (spoil) and to the final disposal of bentonite slurry at the end of the activities. Potentially critical issue seems to be related mainly to the use of polymer-modified bentonites, that will be further explored in this paper.

Concerning railway infrastructures, the construction of retaining structures (piles, micropiles and diaphragm walls) with the use of bentonite and/or polymers will have to be implemented in line with indications contained in the General Technical Specifications for Civil Works, Part II, Sections 7 and 8 (piles and bulkheads). As specified in the specifications for piles and micropiles, the reference standards related to the properties of stabilizing slurries are:

- UNI EN 1536:2015 "Performance of special geotechnical work - Bored piles";
- UNI EN 1538:2015 "Execution of special geotechnical works - Diaphragm walls".

The following Table 1 shows the characteristics of bentonite fluids indicated by the standards given in the RFI contract specifications.

Table 1. RFI standards for bentonite fluids.

| Property | Fresh | Before the use |
|---|---|---|
| Density [g/ml] | <1.10 | <1.25 |
| Marsh viscosity [s] | From 32 to 50 | From 32 to 60 |
| pH | From 7 to 11 | From 5 to 12 |
| Filtercake [mm] | <3 | <6 |

## 2 MATERIALS AND METHODS

### 2.1 *Bentonites and fluids preparation*

To provide a comprehensive comparison between different drilling water-based fluids, different bentonite types were chosen. The bentonites utilized in this activity can be classified as natural sodic (named hereafter "A"), extended with natural polymer ("B") and extended with synthetic polymer ("C").

The fluids were prepared according to the API 13A standard, setting the mixing speed equal to 1200 rpm, using tap water.

### 2.2 *Geotechnical characterization*

To determine the physical and mechanical characteristics of the chosen bentonites, and thus of the drilling fluids, several tests were performed. Specifically, the Atterberg liquid limit was determined for each bentonite using the Casagrande apparatus to establish the moisture content at which the bentonite transitions between plastic and liquid state.

The geotechnical characterization was performed on the fluids at different water/bentonite ratios based on the following tests:

– Marsh funnel viscosity: time, in seconds, for one quart of fluid to flow through a Marsh funnel (UNI 11152-13). This test was performed on fresh fluid and after 24 hours from the fluid preparation;
– density: ratio between fresh fluid mass and its volume, in this case equal to 250 mL;

– fluid loss and filtercake thickness: volume of filtered liquid and thickness of the cake obtained through a filter press set at 7 bar for 22.5 minutes (API 13A). This test was performed on fresh fluid and after 24 hours from the fluid preparation;
– bleeding: volume of water that bleeds from a fluid sample after 24 hours.

### 2.3 *Chemical characterization*

The chemical characterization of the bentonite fluids was conducted according the following methods: pH (CNR IRSA 1 Q 64 Vol 3 1985); Solid residue at 600°C (CNR IRSA 2 Q 64 Vol 2 1984); sulfate concentration (EPA 9030B 1996 + EPA 9034 1996); fluorides concentration (EPA 9056A 2007); chloride concentration (EPA 9056A 2007).

In the technical data sheets the details of the organic molecules, where used, are not reported and specific analysis for their determination were not performed being patented protected commercial products. For this reason, in the present investigation the overall parameters as Total Organic Carbon (TOC) (UNI EN 13137:2002 Method A) and Chemical Oxygen Demand (COD) (ISO 15705:2002) were considered for the evaluation of organic substances concentration in the prepared fluids. In addition, metals concentration (UNI EN 13657:2004 + UNI EN ISO 11885:2009) was provided.

## 3 RESULTS AND DISCUSSION

### 3.1 *Geotechnical results*

The results of the geotechnical characterization are summarized in this section. As shown in Figure 1, the presence of the polymers in the extended formulations (B and C) clearly increases the liquid limit. In all the cases, the limits are above the technical threshold request for drilling operations and such increase in liquid limit provided by the presence of the polymer influences the dosage of bentonite for the preparation of the drilling fluid. In fact, by maintaining the same properties, such as viscosity, the dosage of the extended bentonites is lower than that of the natural one.

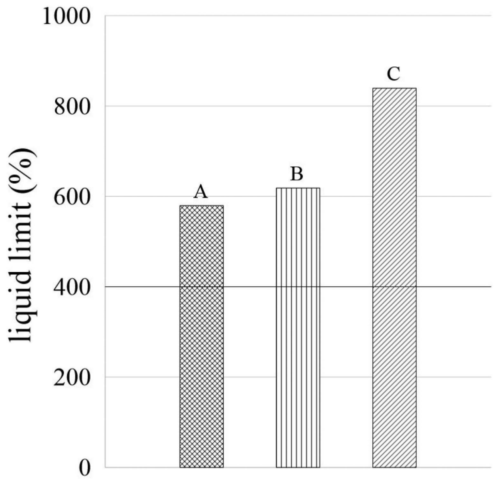


Figure 1. Liquid limit of the bentonite fluids based on natural bentonite (A), extended with natural polymer (B) and extended with synthetic polymer (C).

What previously discussed in term of limit liquid is confirmed by the results summarized in Table 2, where the difference in terms of concentration of bentonite used for the preparation of the drilling fluids is clearly highlighted. In addition, the results of the tests performed on the fresh mixtures are reported in terms of Marsh viscosity, density, fluid loss and filtercake thickness. Even if the bentonite was used at different concentrations, the same trend was observed in all tests; specifically, an increase of Marsh viscosity, density and filtercake thickness was measured with the increase of bentonite concentration while, an opposite trend was recorded in terms of fluid loss.

Table 2. Parameters measured on fresh bentonite fluids.

| bentonite | concentration % | Marsh viscosity s | density g/cm$^3$ | fluid loss mL | filtercake mm |
|---|---|---|---|---|---|
| | 6.04 | 36 | 1.011 | 17.2 | 1.673 |
| A | 7.28 | 41 | 1.013 | 15.2 | 2.040 |
| | 8.02 | 50 | 1.018 | 14.0 | 2.350 |
| | 5.28 | 36 | 1.010 | 16.8 | 1.173 |
| B | 6.04 | 40 | 1.011 | 16.0 | 1.540 |
| | 7.04 | 54 | 1.022 | 14.8 | 1.620 |
| | 3.18 | 35 | 0.990 | 17.2 | 0.740 |
| C | 3.71 | 40 | 0.997 | 16.0 | 0.720 |
| | 4.24 | 47 | 0.993 | 14.8 | 0.906 |

The trends were maintained after 24 h from the fluid preparation (before the use Table 1), as reported in Figure 2. Furthermore, Marsh viscosity (Figure 2a), filtercake thickness (Figure 2b) and fluid loss (Figure 2c) were lower than the thresholds defined by technical requirements discussed above. Measured bleeding was equal to zero for all the tested fluids.

The results of the geotechnical tests, allowed to identify the optimal concentration of the bentonites for the preparation of high performant fluids with a low impact both from economic and environmental perspectives. In particular, the optimal concentrations were 6.04% for bentonite A, 5.28% for bentonite B and 3.18% for bentonite C.

### 3.2 *Chemical results*

During the excavation activities, the excavated soil is in contact with the drilling fluids and, after the final separation, a residue of bentonite can be found into the solid debris. According to the Italian Legislation for the evaluation of soils quality and their reuse, the chemical composition of the soil must be in compliance with specific thresholds (column A of Table 1 in the Annex 5 of D.Lgs, 152/2006 Part IV). For this reason, a general characterization in term of ions and organic substances was conducted to establish possible contaminants that can be found during the drilling operation and the use of bentonite-based fluids (Table 3). Then, a detailed characterization in term of metals (Table 4) is proposed as request by the specification for the excavated soil reuse.

The fluids prepared at the optimal concentration of bentonite founded through the geotechnical investigations, were analyzed to identify chemical properties and composition. The alkaline nature of the fluids is highlighted by the high pH values reported in Table 3 and, from a technical point of view, such values are in line with the limits reported in Table 1. However, in an environmental point of view, such fluid, if not properly prepared, can penetrate the interstitial spaces of the soil causing an environmental alteration with a release of sulphides, sulfates, chlorides and fluorides (Table 3). The presence of polymers in the formulation C allows to reduce the bentonite content and, as a consequence, to reduce the solid residues

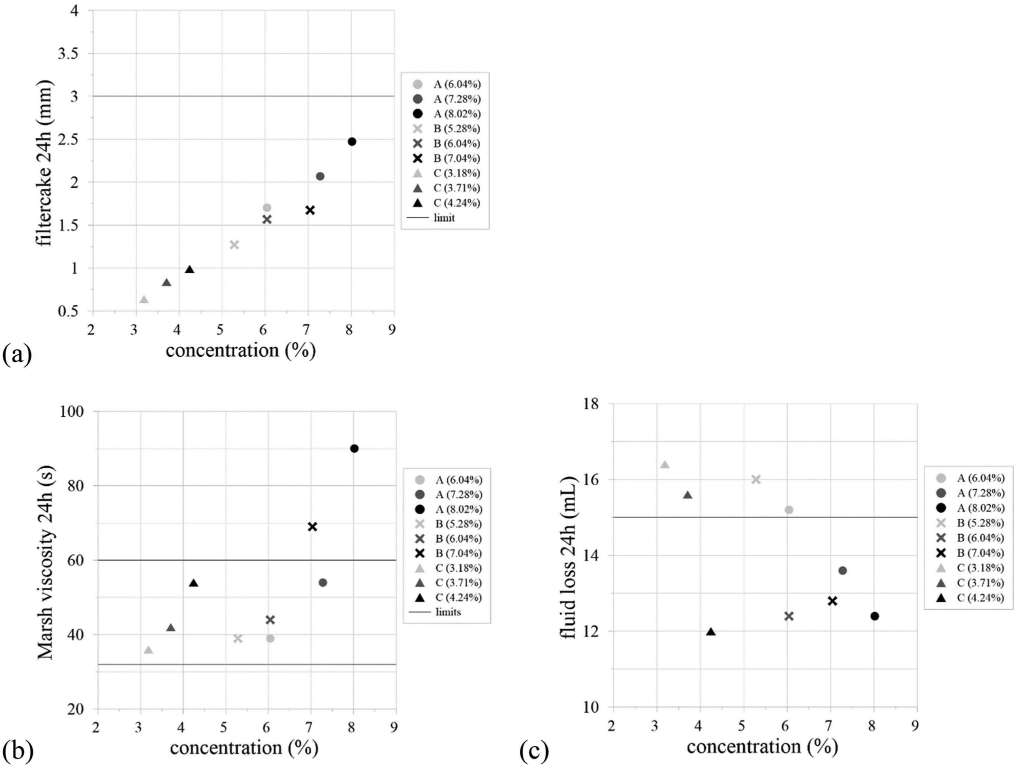


Figure 2. (a) Marsh viscosity, (b) filtercake and (c) fluid loss of bentonite fluids after 24 h.

Table 3. Chemical characteristics of bentonite fluids.

| Bentonite | A | B | C |
|---|---|---|---|
| pH | 10.25 | 9.95 | 9.87 |
| Solid residue (600°C) | 5.04 | 4.11 | 2.89 |
| COD (mg/l) | 308 | 278 | 482 |
| Fluorides (mg/l) | 16.5 | 17.2 | 15.7 |
| Chlorides (mg/l) | 89 | 67 | 73 |
| Sulphide (mg/l) | <0.93 | <0.93 | <0.93 |
| Sulfates (mg/l) | 518 | 508 | 234 |
| TOC (%) | <0.30 | <0.30 | <0.30 |

(evaluated at 105°C and 600°C) and the sulfate content. Interesting are the results in term of COD values: in the fluid C it was observed an increase of the COD of about 56% respect to the natural formulation A. This cannot be associated to the only polymer because no difference in the TOC values was revealed (lower that the detection limit).

The metals found in the bentonite fluids, whose limits concentration in soils are regulated by the D.lgs. 152/2006, are summarized in Table 4. The addition of polymers (natural or synthetic) in the formulations B and C not only contributed to reduce the bentonite concentration but acted as diluting agent of the metals provided by the bentonite itself. In particular, metals as antimony, cadmium, chrome, lead were found with lower concentration in the polymer modified fluids.

Such results are relevant because allow to predict *a priori* the quality/composition of the debris and evaluate its possible reuse. The additional contribution in terms of metals provided by the residual fraction of bentonite can be evaluated by means of a material balance, once the chemical composition of the debris is known.

Of course, this presumptive study must be confirmed by tests with a simulation of debris separation and chemical characterization of debris with bentonite residue.

Table 4. Metal concentrations in the bentonite fluids.

| | Bentonite A | B | C |
|---|---|---|---|
| Metal | Metal concentration (mg/kg) | | |
| Arsenic | 0.839 | 0.879 | 1.3 |
| Antimony | 0.983 | <0.32 | 0.365 |
| Beryllium | <0.059 | <0.057 | <0.05 |
| Cadmium | 0.0959 | 0.0694 | 0.0608 |
| Cobalt | 0.839 | 0.509 | 0.709 |
| Chromium | 1.2 | 0.601 | 0.628 |
| Chromium IV | <0.37 | <0.37 | <0.38 |
| Mercury | <0.14 | <0.14 | <0.12 |
| Nickel | 0.624 | 0.532 | 0.324 |
| Lead | 1.06 | 0.578 | 0.608 |
| Copper | 1.73 | 1.13 | 1..24 |
| Selenium | <0.19 | <0.18 | 0.324 |
| Tin | 0.168 | <0.15 | 0.263 |
| Thallium | <0.22 | 0.231 | <0.18 |
| Vanadium | 4.27 | 4.21 | 3.06 |
| Zinc | 3.74 | 2.27 | 2.13 |

## 4 CONCLUSIONS AND FUTURE DEVELOPMENTS

The objective of this work was to provide a detailed characterization of bentonite-based drilling fluids and to point-out the differences between natural and polymer extended formulation in terms of geotechnical and chemical properties. The geotechnical characterization is necessary for the preparation of a high performant drilling fluid and the chemical one is fundamental for the evaluation of the potential negative impact of drilling fluids during the activities. Moreover, for the purposes of encouraging the reuse of soils and rocks from excavation it is particularly important to evaluate the eventual alteration of the chemical composition of the debris because of the residual traces of bentonite slurries after the separation process.

The presence of the polymers in the bentonite formulation contribute in the reduction of bentonite dosage in fluid preparation without compromising the performances; in a chemical point of view there is a general slight decrease in terms of ions and metals due to the low bentonite content in the polymer extended formulation. In any case, chemical analyses of debris with bentonite residue are necessary to confirm the feasibility of an *a priori* evaluation of debris quality after the drilling operations and separation.

## REFERENCES

Jock Asanja, J., Zaini, M., Surajudeen, A., Aliyu, E.N.U., Omeiza, A.U. (2019), Surface modification of low-cost bentonite adsorbents—A review, Particulate Science and Technology, 37:5, 538–549.

Alemdar, A., Güngör, N., Ece, O. (2005). The rheological properties and characterization of bentonite dispersions in the presence of non-ionic polymer PEG. J Mater Sci 40, 171–177.

Besqa A., Malfoyb C., Pantetb A., Monnet P., Righib D. (2003). Physicochemical characterisation and flow properties of some bentonite muds. Applied Clay Science 23, 275–286.

Anderson, R. W.; Barker, J. R. (1974). Use of Guar Gum and Synthetic Cellulose in Oilfield Stimulation Fluids. Fall Meeting of the Society of Petroleum Engineers of AIME, Houston, TX, October 6−9, 1974; Society of Petroleum Engineers: Richardson, TX, 1974; SPE Paper No. 5005.

Barast, G., Razakamanantsoa, A.R., Maigre, I.D., Nicholson, T., Williams, D. (2017). Swelling properties of natural and modified bentonites by rheological description. Applied Clay Science, 142, 60–68.

Dias, F. T. G.; Souza, R. R.; Lucas, E. F. (2015). Influence of modified starches composition on their performance as fluid loss additives in invert-emulsion drilling fluids. Fuel, 140, 711–716.

Huang, W., Leong, Y-K, Chen, T., Au, P-I., Liu, X., Qiu, Z. (2016). Surface chemistry and rheological properties of API bentonite drilling fluid: pH effect, yield stress, zeta potential and ageing behaviour. J. Petrol. Sci. Eng. 146, 561–569.

Iscan, A. G.; Kok, M. V. (2007). Effects of Polymers and CMC Concentration on Rheological and Fluid Loss Parameters of Water Based Drilling Fluids. Energy Sources, Part A, 29, 939–949.

Kelessidis V. C. (2008). Investigations on the Thixotropy of Bentonite Suspensions. Energy Sources, Part A: Recovery, Utilization, and Environmental Effects, 1729–1746.

Navarrete, R. C.; Himes, R. E.; Seheult, J. M. (2000). Applications of Xanthan Gum in Fluid-Loss Control and Related Formation Damage. SPE Permian Basin Oil and Gas Recovery Conference, Midland, TX, March 23−26, 2000; Society of Petroleum Engineers: Richardson, TX, 2000; SPE Paper No. 59535.

Nunes de, R. C. P.; Pires, R. V.; Lucas, E. F.; Vianna, A.; Lomba, R. (2014). New filtrate loss controller based on poly(methyl methacrylate-covinyl acetate). J. Appl. Polym. Sci. 2014, 131, DOI: 10.1002/app.40646.

Xie, B., Tchameni, A.P., Luo, M., Wen, J. (2021). A novel thermo-associating polymer as rheological control additive for bentonite drilling fluid in deep offshore drilling, Materials Letters, 284, Part 1. 10.1016/j.matlet.2020.128914.

Yan, L.; Wang, C.; Xu, B.; Sun, J.; Yue, W.; Yang, Z. (2013). Preparation of a Novel Amphiphilic Comb-like Terpolymer as Viscosifying Additive in Low-Solid Drilling Fluid. Mater. Lett., 105, 232–235.

Zou Y., Hu Y., Shen Z., Yao L., Tang D., Zhang S., Wang S., Hu B., Zhao G., Wang X., (2022). Application of aluminosilicate clay mineral-based composites in photocatalysis, Journal of Environmental Sciences, Volume 115, 190–214.