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Properties of Cement Composites Utilizing of Bentonite: A Review

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***Abstract*-The use of bentonite clay slurries in civil and geotechnical engineering dates back to Veder's pioneering work in 1953. Since then, bentonite has been used for various applications such as the construction of bored piles and diaphragm walls. Plastic concrete walls also require sufficient strength and modulus to adapt to the surrounding environment, and the characteristics and different forms of bentonite commercially available were reviewed in this paper.**

This paper reviews the properties and applications of bentonite, including its use in cement-bentonite composites for remedial cut-off wall construction. Cement-bentonite grouts offer advantages over bentonite grouts in terms of ease of use and adjustability of strength.

Cement-bentonite composites were found to be promising materials for remedial cut-off wall construction due to their ability to meet requirements for strength, stiffness, and permeability. By regulating the mix proportions, the strength of the set grout can be adjusted to match that of the surrounding ground. Cement-bentonite grouts also offer advantages over traditional bentonite grouts, as they are easier to use, offer a longer working period before setting, and can be forgiving if the user deviates from the design formula or the mixing technique. This paper provides useful information for those working with bentonite and cement-bentonite composites in civil and geotechnical engineering applications.

***Keywords*-Bentonite, chemical properties, physical properties, slurry, cement mortar.**

I. INTRODUCTION

Bentonite is a valuable material for various industries, including electric, ceramics, painting, pharmaceuticals, cosmetics, filtering agents, household products, and detergents [1]. In civil engineering, bentonite support fluids are commonly used due to their low permeability and high deformability [2].

Vertical cut-off walls are a reliable anti-seepage technology used in civil engineering for their simple design, ease of operation, cost-effectiveness, and good watertightness. Bentonite is also used in plastic concrete for earth dam cut-off applications due to its ability to withstand applied stresses [3].

However, there are problems associated with leakage of the dam foundation, leakage around the dam, contact erosion, and piping, which threaten the safety of earth-rock dams. Building vertical cut-off walls with bentonite can help address these issues. Additionally, further research and development are needed to address challenges related to the use of bentonite in different applications [4].

Cement-bentonite composites have gained popularity in construction, particularly for remedial cut-off wall construction. They are designed to satisfy requirements for strength, stiffness, and permeability. Cement-bentonite grouts are also simpler to use compared to bentonite grouts and offer longer working periods before setting. They are used to regulate cement amounts and adjust mix proportions to match the strength of the surrounding ground. Additionally, there are studies on the mechanical properties and performance evaluation of the bentonite-PVA fiber cement-based composite material for construction. Other applications include soil-cement-bentonite slurry walls and slag-cement-cement-bentonite slurry walls [5].

II. BENTONITE DEFINITION AND PROPERTIES

Bentonite is a weathered rock composed of clay-like minerals that can swell and gel when dispersed in water, while also exhibiting Pozzolanic properties [6, 7]. It is named after the location where it was first discovered in 1898, Fort Benton Eastern Wyoming in the United States, and is composed primarily of the mineral montmorillonite, which is part of the smectite group [8-10]. Structurally, montmorillonite ($\geq$ 80 wt.%), is classified as a 2:1 layered aluminosilicate, consisting of one AlO6-octahedral sheet between two SiO4-tetrahedral sheets [1, 8, 11-15].

There are three common types of bentonite, namely [2]:

- Natural sodium bentonite (Na-Bentonite)
- Natural calcium bentonite (Ca-Bentonite)
- Sodium-activated bentonite

Sodium-activated bentonite is produced by adding soluble sodium carbonate to Ca-bentonite, which replaces the calcium ions on the surfaces of clay particles with sodium ions, resulting in a bentonite exhibiting many typical characteristics of natural Na-bentonite. The result can vary in swelling capacity, with Na-bentonite having high swelling, Ca-bentonite having low swelling, and Ca-Na-bentonite having medium swelling [16]. Figure 1 shows the intracrystalline swelling of bentonite.

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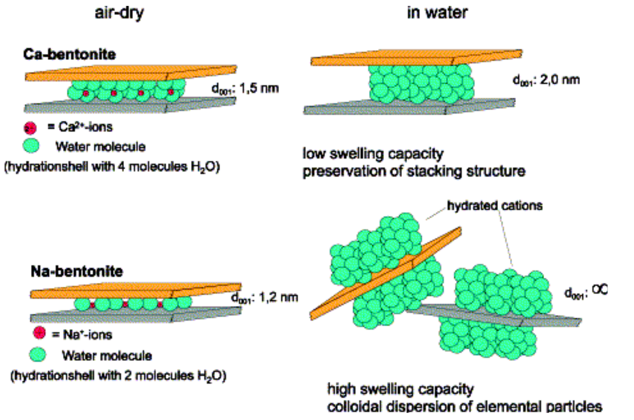

Figure 1. Intracrystalline swelling of calcium and sodium bentonite [17].

A. *Chemical properties of bentonite*

Bentonite is considered a type of clay mineral and can be classified as a hydrous aluminum silicate or alumino silicate. Specifically, montmorillonites belonging to the smectite group are the type of clay minerals that are typically found in bentonite [18] (as seen in Fig. 2). These montmorillonite particles are composed of two tetrahedral sheets (Si-O) framing an octahedral sheet (Al-O-OH) [1, 19], which gives them a net negative charge [16]. The chemical composition of bentonite used in various researches can be found in Table 1.

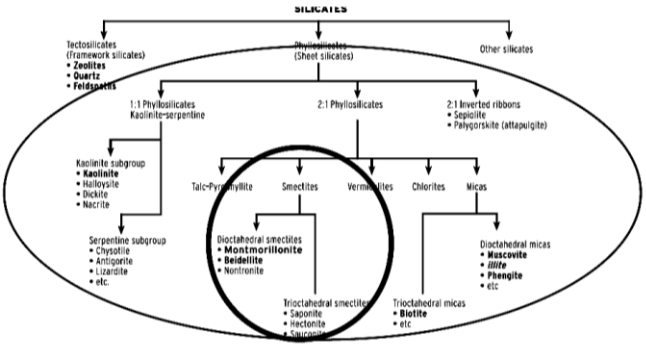

Figure 2. Classification of silicates and bentonite [18].

Table 1. Chemical compositions of bentonite used in various researches

Composition%	References								
	[3]	[16]	[20]	[21]	[22]	[23]	[24]	[25]	
	Na		Ca		Na	Na	Ca	Na	Na
SiO_2	70.12	56.37	72.02	58.64	63.26	59.1	57.83	63.04	64.78
Al_2O_3	12.19	17.4	15.76	15.24	17.35	17.7	13.55	17.15	13.74
Fe_2O_3	4.12	1.84	1.44	3.96	5.34	-	5.94	3.17	4.1
MgO	0.07	2.78	3.27	2.39	3.12	2.03	2.44	4.12	2.79
CaO	3.52	1.39	2.19	4.48	3.6	2.89	3.97	1.93	4.5
Na_2O	2.16	3.21	0.22	3.22	4.36	-	-	2.64	1.93
K_2O	1.43	1.7	0.38	1.02	1.2	1.85	1.59	1.47	1.5
TiO_2	0.25	0.1	0.21	-	0.61	-	-	-	-
P_2O_5	-	.03	-	-	-	-	-	-	-
LOI	5.12	15.08	-	-	-	-	10.17	-	-

B. *Physical properties of bentonite*

Bentonite is generally available in different colors and forms, and some authors have reported the colors of greenish gray and browning green [26], or light yellow [27].

Table 2 provides an overview of the physical properties of bentonite reported by different authors, and these values may differ due to variations in the source location [9, 10]. Sodium-activated bentonite can adsorb more water than Ca-bentonite [30], with Na-bentonite capable of absorbing up to 600-700% of water while Ca-bentonite can adsorb 200-300% of water [19, 33].

This water adsorption capacity causes the clay minerals, especially montmorillonite, to significantly increase in volume. While other water-binding additives, like sepiolite or silty clay, can be used to produce Plastic Concrete [31, 34], bentonite remains important due to its heavy metal absorption capacity, which makes it useful for creating containment barriers for wastewater and radioactive waste [9, 31, 34, 35].

The important market for bentonite exists in civil engineering techniques such as sealing buildings, constructing dams and tunnels, laying pipes, and creating special foundations like diaphragm walls and piles. The rheological behavior of these systems is critical for effective use in engineering field [16]. In industry, bentonite is extensively used in drilling fluids to modify the rheology and control the stability of liquid systems [36-41].

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Table 2. The overview of physical properties of bentonite reported by some authors

Property	References												
	[28]	[4]		[16]	[22]	[23]	[29]	[30]	[20]	[31]	[29]	[25]	[32]
Specific gravity	-	-	-	-	2.7	2.56			1.1 (Ca)	3.05	2.35	2.44	2.8
Average particle size (µm)	-	-	-	0.2-200	-	-	#200 (%) 100	-	-	-	80	80	-
Blaine fineness (cm^2/g)	-	-	-	-	530 m^2	7500	-	-	-	220 m^2	4371	4286	87.5 m^2
LL (%)	-	532.9	387	-	-	-	293	-	-	210	-	-	410
PL (%)	-	68.21	47	-	-	-	64	-	-	105	-	-	45
Plasticity index Ip%	75.6	464	340	-	-	-	229	-	-	105	-	-	365
Viscometer dial reading at 600 rpm: R600	15	-	-	-	-	-	-	-	-	-	-	-	-
Viscometer dial reading at 600 rpm: R300	10												
Plastic viscosity (ηp)	5	-	-	-	-	-	-	-	-	-	-	-	-
Permeability	-	-	-	-	-	-	-	10^{-8}		$1.3x10^{-8}$	-	-	-
Water absorption %	-	-	-	-	-	-	-	-	165		-	-	-
Color	-	-	-	-	-	-	-	-	-	Gray to light green	-	-	-
Conductivity (us/cm^2)	-	-	-	-	-	-	-	-	-	-	-	-	10800
pH	-	-	-	-	-	-	-	-	-	-	-	-	7.4

III. TECHNIQUES OF BENTONITE APPLICATION

Cement-bentonite composites have a range of applications in civil and geotechnical engineering. These include:

1. Groundwater control: Cement-bentonite slurries can be used to create self-supporting, low-permeability barriers for groundwater control.
2. Hydraulic containment: A mixture of water, cement, and bentonite is commonly used for hydraulic containment applications due to its low permeability.
3. Cutoff walls: Cement-bentonite slurry trench cutoff walls are used for seepage control and have advantages over other techniques such as grouting and sheet-piling.
4. Contaminated land containment: Cement-bentonite is commonly used for contaminated land containment applications [**42**], but challenges related to its use still exist.
5. Soil injection: Bentonite-cement composites have been used for soil injection applications.
6. Reactive MgO-based self-healing slag-cement-bentonite slurry walls: These composites are used for geotechnical and geoenvironmental applications.
7. Slurry walls: Cement-bentonite and slag-bentonite cutoff walls have been investigated for their performance in different applications [**43**].

A. Bentonite- soil stabilization

Soil stabilization aims to bind soil particles together to form a rigid, load-bearing mass that can resist the effects of weathering. Adding lime to expansive clays such as bentonite can help reduce the plasticity index and increase the load-bearing strength [**32**]. It was found that bentonites required at least 8% lime as the optimum amount for stabilization, while for kaolins the optimum amount was about 4%. This information suggests that lime can be used effectively to improve the load-bearing strength of certain types of soil, including bentonite clay [**44**]. However, more detailed information about soil stabilization techniques may be available in other sources or through further research.

B. 3.2 Bentonite grouts

Grouting is a common technique used in geotechnical engineering to either reduce the permeability of soil and rock or to improve their mechanical properties. This technique involves injecting a mixture of cement, bentonite, or other materials into the ground to stabilize it. Success in a grouting operation requires that the desired improvements in the properties of the formation are attained. Cement grouting has been identified as a possible solution for improving the properties of shallow soil, and bentonite has been found to be a cheap and effective admixture for cement grouts, which can potentially improve stability [**30, 32**]. This finding challenges the common perception that only bentonite slurry can stabilize very coarse soil [**45**].

A bentonite grout composed of only bentonite and water may not be volumetrically stable and can create uncertainty about locally introduced pore water pressures caused by the hydration process. However, the addition of cement, even in small amounts, can reduce the expansive properties of the bentonite component once the cement-bentonite grout takes an initial set. It is easier to adjust the mix for variations in temperature, pH, and water cleanliness with cement-bentonite grouts. They are also easier to use, provide long working times, and are more forgiving if the user deviates from the design recipe or mixing equipment and method. On the other hand, pure bentonite grouts must be mixed and deployed by strictly following measured quantities and procedures not commonly done by drillers doing test borings. Cement-bentonite grouts are a more practical and effective option for some geotechnical engineering projects [**46**].

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Thixotropy in bentonite slurry is due to the orientation of plate-like particles within the slurry, resulting in the formation of an interlocking structure due to electrical bonding forces between them. This causes the slurry to form a gel when allowed to stand. However, on agitation of the gel, the electrical bonds are broken, and the slurry becomes fluid with randomly oriented particles. This phenomenon occurs when 3% or more bentonite powder is mixed with water [**2**].

Water and powdered bentonite mixed into a slurry-like drilling mud, which is made denser with the help of additives and specialized grout mixing units. As the bentonite solids-content increases, the permeability decreases. However, such slurry has a high-water content and never really sets up to a solid form like chip-seals. Despite the availability of various bentonite sealing grouts, none of them set up to a solid form. Over-mixing can lead to a flash set, and pumping such grouts through small diameter grout pipes can be difficult. The working time of these grouts is too short and diluting them can lead to a permanently soupy backfill [**30**].

The use of clay chemical grouts has proven to be effective in alluvial soils and for treating the ground for tunnel passage under river estuaries where the set gel's resistance to acid and alkali attacks is advantageous in the presence of salt water [**45, 47**].

C. Bentonite-cement slurry

Rafalski, **1994** [**48**], investigates the composition of bentonite-cement slurry for cut-off walls. The procedure involves determining the cement to bentonite slurry ratio, evaluating the bentonite and cement content in the slurries, and the modifier content (sodium bicarbonate and disodium phosphate mixture). The study estimates the relationship between compressive strength and CS/BS ratio of the specimens with bleeding less than 5%, as RS = l.806(CS/BS) - 0.19 (CS/BS ratio ranged from 0.1 to 0.8).

A 9.1% solid bentonite slurry was utilized in place of some cement and pre-made foams in foamed concrete with dry bulk densities of 300 and 600 kg/m^3. The fluidity of the new pastes increased with the addition of bentonite slurry and then decreased when the amount of bentonite slurry was increased. Although compression strength reduced as bentonite slurry content increased in foamed concrete with a dry bulk density of 300 kg/m^3, thermal insulation properties dramatically enhanced. For dry bulk densities of 300 kg/m^3 and 600 kg/m^3, respectively, foamed concrete showed lower thermal conductivity values of 29.8% and 15.3% [**48**].

Furthermore, bentonite slurry may be used to create a closed-cell honeycomb nano scaled pores in foamed concrete [**49, 50**].

D. Cement-Bentonite grouts

Adding cement, P.F.A., or fillers like silt, local clays, China or ball clays, or sand to neat bentonite suspension can improve its gel strength for use in open voids and fissures. Hydrated bentonite helps prevent settlement and segregation of the filled grout. Cement-bentonite grouts are impervious, easier to use, and a more economical choice than neat cement grouts [**30**, **46**].

Cement-based grouts have been effectively utilized for repairing cracks in various concrete structures, providing stability to slopes and retaining walls, and strengthening rock or soil foundations [**16**].

Using a bentonite grout backfill composed only of bentonite and water may not be volumetrically stable and can create uncertainty about locally introduced pore water pressures due to the hydration process. However, adding even a small amount of cement to create a cement-bentonite grout can reduce the bentonite's expansive properties once the initial set occurs. The strength of the grout can be adjusted by controlling the cement content and mix proportions to match the surrounding ground. Cement-bentonite grouts offer a longer working time before setting, are more forgiving if the user deviates from the design recipe or mixing equipment/method, and easier to adjust for variations in temperature, pH, and water cleanliness compared to bentonite grouts [**30**].

Sodium bentonite produces lower permeability slurry than calcium bentonite and the partial replacement of cement with GGBS reduces permeability by 1 to 2 orders of magnitude [**51**].

E. Plastic concrete

Plastic concrete is used in various structures, such as cutoff walls, cutoff curtains, grouting, and vibrating damping walls, to prevent the spread of pollutants from industries into underground waters, control seepage under dam foundations, and build cutoff walls [**4**]. Slurry walls made of either traditional or plastic concrete are widely used in geotechnical engineering for both structural and hydrogeological purposes. These walls are used in various civil engineering applications, including tunnels, dams, reservoirs, and dewatering plans, to stop or improve groundwater flow, as well as to confine underground-polluted sites.

In dam engineering, cut-off walls made by plastic concrete are utilized for constructing slurry cut-off walls in highly porous dam foundations [**52**]. The primary function of a plastic concrete cutoff wall is to serve as a barrier to prevent or reduce groundwater flow.

The constituents of plastic concrete include cement, aggregates, water, clay, and bentonite, which is mixed at a high-water cement ratio to provide ductility [**4, 53-55**]. Plastic concrete has a lower cement content compared to ordinary concrete and contains clay and bentonite [**20**]. It is an intermediate material that does not behave entirely like conventional concrete or soil [**56**].

Water tightness and flow management are critical concerns in dam design and construction [**1, 3, 10**]. Plastic concrete can aid in creating watertight structures and consists of materials that enhance its flow-management capabilities [**4**].

According to **Mahboubi et al.** [**52**], plastic concrete cut-off walls must have sufficient strength and proper modulus to adapt to the surrounding geoenvironments. They researched the appropriate elastic modulus of a plastic concrete cut-off wall and recommended that the cut-off wall and surrounding

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soil should have an elastic modulus of the same order of magnitude. The International Committee of Large Dams (ICOLD) recommends that the elastic modulus of the plastic concrete cut-off wall be one to five times that of the surrounding soil, as per [**3, 57**].

IV. CHARACTERISTIC OF CEMENT-BENTONITE COMPOSITES

A. Rheological properties

Tests examined how cementing materials like bentonite, colemanite ore waste (CW), coal fly ash, and coal bottom ash affect cement and concrete properties. Results showed that substituting cement with bentonite accelerated the setting time but combining it with CW at lower replacement levels delayed it and accelerated it at higher levels [**24**].

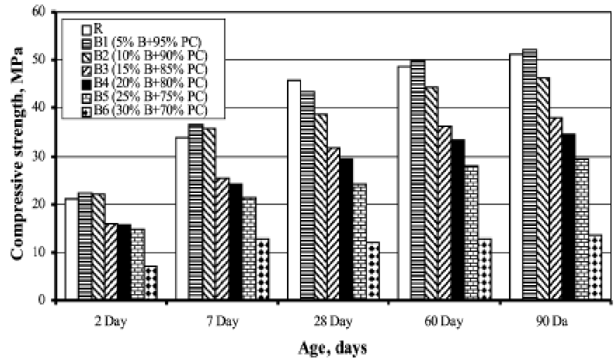
The effects of bentonite, fly ash, and silica fume on bleeding in high-performance concrete using the Taguchi approach were conducted [**58**]. The study aimed to find the optimal conditions for different water-to-solid ratios (0.75, 1, and 1.25) by varying the percentages of bentonite (0-3%), fly ash (10-40%), and silica fume (0-20%). The results indicated that the optimal conditions for 0.75 and 1.00 water-to-solid ratios were found to be 20% silica fume, 3% bentonite, and 10% fly ash, while for a 1.25 water-to-solid ratio, it was 20% silica fume, 3% bentonite, and 20% fly ash. The study suggests that adding bentonite, fly ash, and silica fume in specific proportions can help to reduce bleeding in high-performance concrete, leading to improved durability and strength.

Mixtures with varying levels of bentonite content (8-18%) were subjected to physical and rheological tests, which resulted in a reduction of cement grout fluidity from 14 cm to 6 cm. This was caused by the specific surface of bentonite and its unique structure causing clay particles to absorb water, hindering lubrication of particles [**16**]. The results agree with other studies [**59-61**]. The montmorillonite particles have flat platelets and form two structures: "card-house" and "card-pack" [**60**].

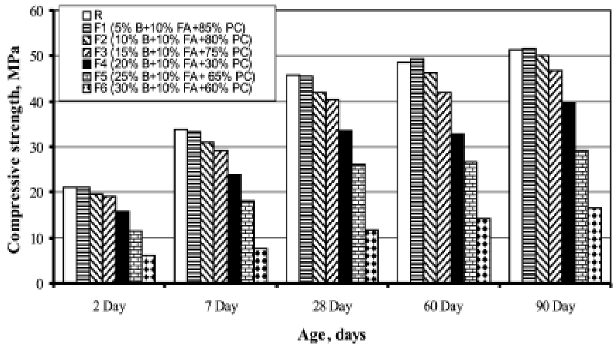
B. Mechanical properties

Table 3 presents some of the selected properties of cement-bentonite mixtures in various researches.

The inclusion of bentonite at replacement levels of cement at 5-10% increased compressive strength at early ages, it decreased compressive strength when used in combination with other materials [**24**]. **Figure 3** shows the effect of using different content of bentonite as replacement of cement by weight as well as the effect of using fly ash.



a- Effect of bentonite content %



b- Effect of bentonite content % and 10% fly ash

Figure 3. Effect of using bentonite and fly ash on compressive strength at different ages [24].

Pisheh and Hosseini (**2019**) [**29**] conducted a study to investigate how incorporating bentonite into concrete mixes affects unconfined uniaxial compressive strength and confining pressure stress-strain curves (at 350 kPa). The results presented in **Table 4** and **Fig. 4** show that as the bentonite content increased, the peak point and slope of the linear portion of the stress-strain curve (which respectively represent material compressive strength and elastic modulus) decreased. This is believed to be due to the role of bentonite particles in weakening the bonds between cement material and aggregates, as well as decreasing the rate of cement hydration in the specimens.

Table 4. Mix proportions of the plastic concrete samples [29]

Mix ID	*B/C* ratio	*C* (kg/m³)	*B* (kg/m³)	*W* (l/m³)	*S* (kg/m³)	*G* (kg/m³)
S1	0.21	140	30	252	730	860
S2	0.29	140	40	252	730	860
S3	0.14	140	20	252	730	860
S4	0.21	140	30	252	630	960
S5	0.21	140	30	252	530	1,060
S6	0.27	110	30	198	730	860
S7	0.18	170	30	306	730	860

Note: Water/cement ratio for all mixture designs = 1.8; *B* = Na-bentonite by mass per m³; *C* = cement by mass per m³; *W* = water volume per m³; *S* = sand aggregates by mass per m³; and *G* = gravel aggregates by mass per m³ of plastic concrete.

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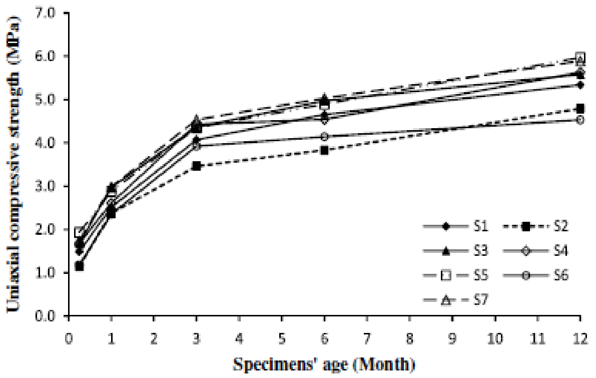
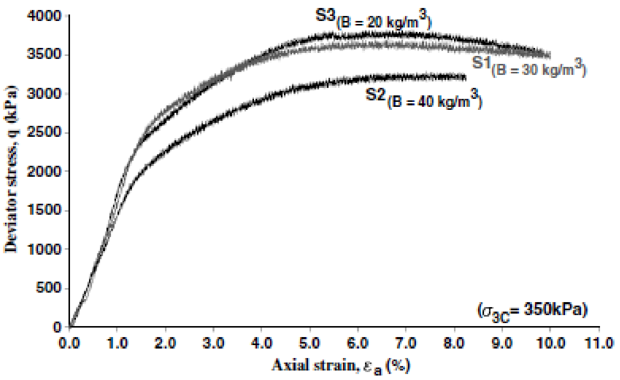


a- Uniaxial compressive strength at different ages

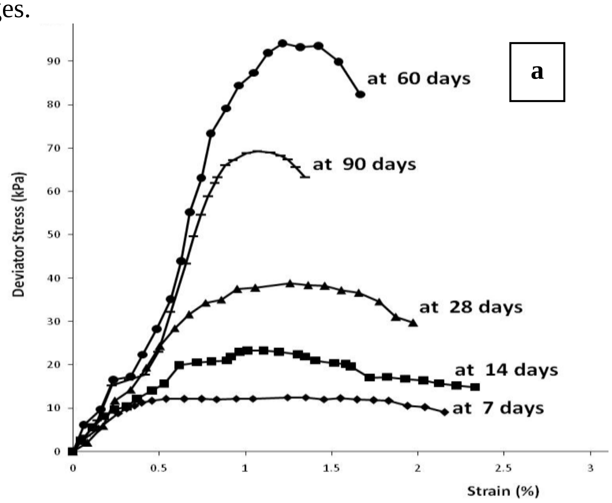


b- Stress strain relationship

Figure 4. Effect of bentonite on plastic concrete behavior [29].

Alzayani et al. (**2016**) [**63**] conducted a review study which comparing the deformation behavior of cemented particulate systems commonly encountered in civil engineering, including cement-bentonite, and found that microcrack formation before reaching peak strength has not been studied with cement-bentonite materials. This could potentially have a significant negative impact on the ability of a cement-bentonite barrier to retard groundwater migration. As a result, further research is needed to determine if microcracking in cement-bentonite poses a significant hazard.

Figure 5 depicts the stress-strain behavior of cement-bentonite with different cementitious materials at different ages.



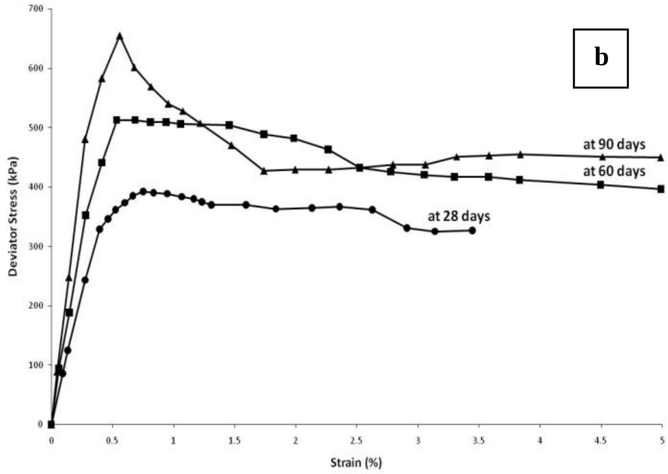
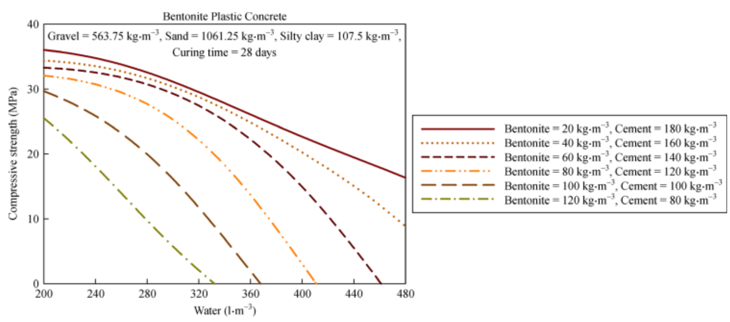


Figure 5. Stress-strain behavior of cement-bentonite
a- samples in unconfined compressive strength (Mix design used: 40 g of bentonite and 200g of cementitious material per litre of water (with 28% PFA as cement replacement) [Royal et al. (2013)] [64]
b- samples containing 80% GGBS in undrained triaxial tests at 0.4 mm/min at 60 kPa confining pressure, after Williams and Ghataora (2011) [65].

There have been numerous studies on the strength of cement-bentonite composites. Studies suggest that the unconfined compressive strength of soil-cement-bentonite backfill ranges from 30-150 psi (0.2-1 MPa), while the permeabilities are typically in the range of 10^{-7} cm/sec.

Research has also examined the compressive strength of bentonite plastic concrete samples by using machine learning [**66, 67**]. **Figure 6** illustrates some of finding of the results.

Basalt fiber contents (0-.8%) and lengths (3-12 mm) were studied on the mechanical properties of bentonite cement paste [**68**]. The addition of basalt fiber enhanced unconfined compressive strength and splitting tensile strength at an optimum content of 0.6%, increasing with curing age. The optimum basalt fiber length for improving strength was 9 mm. These results suggest that adding basalt fiber is a promising way to enhance the mechanical properties of bentonite cement paste.



a- versus water

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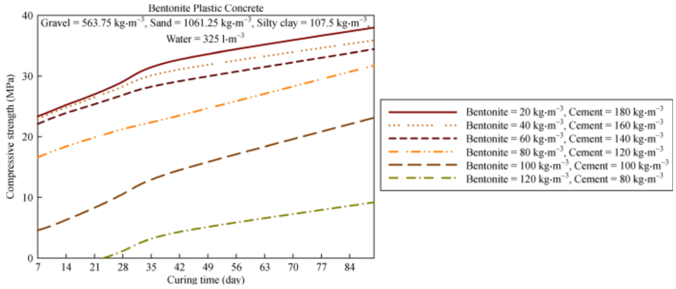

b- versus curing time

Figure 6. Variations of compressive strength of plastic concrete with different cement and bentonite [66].

The use of complex agents like Odolit-K in combination with bentonite to achieve high-strength fine-grained cement composite materials was reported [**69**]. The strength of the composite may also be affected by the addition of different materials such as high-volume fly ash, basalt fibers, and anti-microbial compounds.
Figure 7 shows the effect of confining pressure on the failure mode in sedimentary rocks.

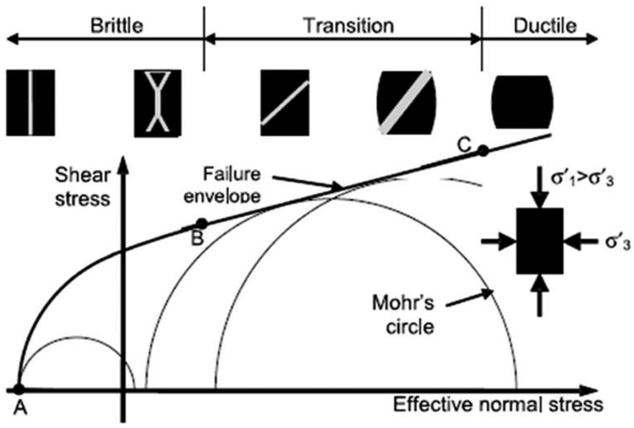

Figure 7. Effect of increasing effective confining pressures on the failure modes and fracturing of sedimentary rocks [61].

C. 4.3 Permeability and hydraulic conductivity

Besides, different studies suggest that the permeability of soil or sand can be reduced significantly by adding bentonite. the CSH gel produced by cement hydration can link with bentonite to form a dense microstructure, which is attached to the surface of sand grains and fills the pores between sand grains, thus reducing the permeability of the sand and achieving seepage prevention and plugging [**70**].
Currently there is no specific testing standard to measure the permeability of Plastic Concrete, even though it is an important parameter to test since seepage control of earth dams is the primary purpose of a cut-off wall [**9**]. As a result, standard test methods from geotechnical engineering and concrete technology are employed. Hydraulic conductivity testing of concrete specimens can be divided into two main categories: loaded and unloaded conditions. In concrete technology, it is common to test material hydraulic permeability without simultaneous loading. **Hoseini et al.** (**2009**) [**71**] and other researchers have reviewed this approach [**9**].
The hydraulic conductivity can be derived from Eq. (**1**). The relationship between the permeability and hydraulic conductivity is stated in Eq. (**2**) [**3**]:

$$K_T = 2.3 \times \frac{aL}{A(t1 - t2)} \log \frac{h1}{h2} \quad (1)$$

$$K_T = \frac{kg}{v} \quad (2)$$

Where:

K_T is the hydraulic conductivity (m/s), a is the section area of the piezometer (m^2), A is the section area of the sample (m^2), L is the height of the ring knife (m), $t1$ is the end time of the determination (s), $t2$ is the start time of the determination (s), $h1$ is the water head before the determination (m), $h2$ is the water head after the determination (m), g is the gravitational acceleration (m/s^2), k is the permeability (m^2), and v is the kinematic viscosity (m^2/s).
He et al. (**2020**) [**3**] studied a modified plastic concrete cut-off wall by varying the mass ratios of silica fume between 0-21.3%, while keeping the cement content constant at 8%, based on a conventional soil-bentonite cut-off wall. They analyzed the slump test, hydraulic conductivity, and mechanical performance to determine the ideal material ratio. The optimal sample had a hydraulic conductivity (~10^{-9} m/s) that met the anti-seepage requirement and the amended plastic concrete cut-off wall had appropriate compressive strength (0.896 MPa) and a low elastic modulus (1244.5 MPa). The clayey soil materials and modified plastic concrete cut-off walls were analyzed by X-ray diffraction methods, revealing that the clayey soil primarily contained quartz and feldspar (specifically anorthite).

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Table 3. Properties of cement- bentonite composites as given in previous studies

Ref. No.	Type of composites	Ratio %	Properties of bentonite	Tests	Main results
Rafalski, 1994 [**51**]	Bentonite-cement grouts		bentonite 1 of *WL* = 161%, • bentonite 2 of *WL* = 187%, • bentonite 3 of *WL* — 211%.	Structural requirements: Strength, deformability, permeability and chemical resistance Technological Requirements: - density *p*, - apparent viscosity *rj*, - gel strength *TF*, - bleeding *O*, - time of liquidity *TL*, - setting time *T$*.	Linear relationship between compressive strength of bentonite-cement *RS* with bleeding less than 5%: *RS* = *l.806(CS/BS)* - 0.19 and cement slurry / bentonite slurry ratio is observed, and its coefficient of correlation is higher when concentration of solid components in the bentonite-cement slurries does not grow significantly during the setting process because of bleeding.
Awad et al., 2003[**60**]	Bentonite-cement grouts		Plasticity index= 146.31%, clay content= 86.35%, activity 1.69, free swell=130%, specific gravity= 2.82	Shear strength characteristics along the interface surface between the bentonite-cement grout in sandy soil by using direct shear test and unconfined shear procedures	Angle shear resistance as effective diameter of sand, time of curing, sand density increases and bentonite content decreases. - adhesion of the bentonite-cement-grout-sand interface decreases as bentonite content increases up to 30% bentonite
Kim and Kim, 2016 [**23**]	cement-stabilized sand–bentonite	CSB; cement 10%, bentonite 0-20%, nylon fiber 0-2%, metakaolin 0-2%	- Bentonite with a specific surface area (SSA) of less than 7,500 cm2/g and a specific gravity (SG) of 2.56 was employed to create the CSB mixes. - Soil L.L 33.9%, plasticity index NP	- Unconfined compressive strength (UCS) (3,7,28 days) - splitting tensile strength (STS) (3,7,28 days)	The highest improvements in UCS and STS were all achieved in the CSB combination with 10% bentonite content, while the addition of 1% fibers and 1% metakaolin to the same CSB mixture resulted in increases in UCS of roughly 40% and 70%, respectively.
Pisheh and Hosseini, 2019[**29**]	Concrete Cutoff Walls' Mechanical Behavior with Plastic Concrete	- Bentonite content 14-29% by cement -Confining pressures 200, 350, and 500 kPa - Cement content - G/S - Ages - curing conditions	Na-bentonite: LL 293%, PL 64%, PI 229%	- Unconfined compression (7-350 days) 6 MPa - Triaxial compression - Modulus of elasticity - Failure Envelopes and Shear Strength Parameters (C^- = effective cohesion parameter; ϕ^- = effective internal friction angle; Cu = undrained cohesion parameter; and ϕu = undrained internal friction angle) - Failure Mode of the Specimens	Based on the mix design and confining pressure acting on the specimens, the manner of failure in the various samples ranges from bulge-shaped sides to entirely distinct shear bond.
Kazemian et al., 2016 [**4**]	Plastic concrete	- Bentonite types (1, 2) - Water: bentonite (17:1) - Cement content (90, 100, 120, 130, 140, 150, 200) - Marsh (sec) (37, 38, 52, 53, 54) - Coarse aggregate/ fine aggregate (0.56, 0.63, 0.65, 0.79, .8, 1.13)	- Bentonite 1 (PI= 464%) - Bentonite 2 (PI= 340%)	- Marsh - Compressive strength - Elastic modulus	- Elastic modulus (2381-13750 kg/cm2 for 80-150 kg/m3 cement content) - Compressive strength 3.84-14 kg/cm2 for cement content 80-150) - Marsh has versa effect on compressive strength - Bentonite with high activity has the highest effect on increase the compressive strength)
Shilpa and Sasindran, 2018 [**62**]	Concrete with calcium bentonite as partial replacement of cement and fine aggregate with steel slag	- Proportion of (0% to 20%) calcium bentonite - 40% of steel slag as fine aggregate	For each replacement, the typical consistency of 31% is maintained.	Workability, compressive strength (7,28 days), splitting tensile strength (7, 28 days), flexural strength (28days), Ultra Sonic Pulse Velocity (7, 28 days), acid attack	- 10 % replacement of cement with CB and 40% replacement of M-sand with steel slag gave higher compressive strength (37.7 MPa) (23.29%) than plain concrete - In acid attack test the specimen with 10% CB and 40% steel slag shows 17.96% lesser weight loss when compared with the plain concrete and 10.45% lesser weight loss when compared with the concrete having 0% CB and 40% SS

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V. Conclusions

This paper reviews the properties and applications of bentonite, including its use in remedial geotechnical and construction applications and the following conclusions can be drawn:

1. Seepage control is crucial for the safety of earth dams and so on, with rigid concrete cutoff walls being a common method. However, earth embankment deformation can cause wall rupture, highlighting the need for strong, watertight and soils-comparable materials. Strain compatibility between wall and surrounding soil is also essential. Materials include soil-bentonite mixtures, asphaltic concrete membranes, geosynthetics, and various rock materials, but site-specific design is recommended in selecting the most appropriate material. Further consultation with experts is advised.
2. Plastic concrete, which consists of the same materials as normal concrete, with the addition of clay or bentonite and a high water-cement ratio, can increase ductility and improve the resistance to cut-off wall deformation. This type of concrete may meet requirements for cut-off wall construction, such as strength, stiffness, and permeability. The properties and potential applications of plastic concrete are discussed in some of the search results, with one study investigating the mechanical properties of plastic concrete containing bentonite.
3. Substituting cement with bentonite can affect the setting time, and combining bentonite with other cementitious materials can either delay or accelerate the setting time depending on the replacement level. The addition of bentonite to cement composites can improve rheological properties and shape retention, which can lead to appropriate mechanical properties in the product.
4. The deformation behavior of cemented particulate systems encountered in civil engineering, including cement-bentonite barriers. The microcrack formation prior to reaching peak strength could potentially have a negative impact on their ability to retard groundwater migration.
5. There is currently no specific testing standard to measure the permeability of Plastic Concrete, even though it is an important parameter to test since seepage control of earth dams is the primary purpose of a cut-off wall. As a result, standard test methods from geotechnical engineering and concrete technology are employed.
6. Other materials such as epoxy lining, calcium aluminate cements, smart coatings, .. etc. are mentioned in the literature for water distribution system construction, nuclear facility decontamination, and material protection. Studies also exist on unsaturated soils' tensile strength and amorphous solids' deformation and flow. However, no information is found about plastic concrete's properties or potential applications.
7. Further testing and research are needed to develop better guidelines for selecting grout mixes for sealing piezometers in boreholes. However, it is recommended to consult specific publications or experts in the field for more detailed guidance on this topic.

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