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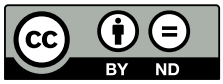

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1 Introduction

Hardening slurry is a composition of water, bentonite, setting material (mostly cement) and chemical admixtures modifying properties of liquid or hardened slurry (if needed).

Before the setting process starts, the slurry has the same properties as drilling slurry, which keeps up the stability of a trench or hole drilled in the ground. After the cement sets and the completion of the curing cycle, the slurry forms the material with determine strength parameters. This slurry enables the foundation of prefabricated products (reinforced concrete and steel) in the ground or can constitute constructional material for cut-off walls.

The last of the above mentioned applications may be used in hydraulic engineering during the erection of new objects as well as the restoration of old dams. For instance it can be used for sealing earthen dam subsoil and as a sealer between a concrete structure and the ground.

The technology of hardening slurry cut-off walls makes restoration possible without negative influence on existing concrete elements during the practically continuous exploitation of the reservoir. Any corrections can be made easily and uniformity of the built-in material is guaranteed.

The research works on hardening slurries were begun quite recently, in the 1970's in France. Until this time, research was focused on cement-bentonite slurries or slurries made from cement, bentonite and an other binder or sealer. Both were tested without chemical admixtures and with them.

Due to a wide variety of chemical admixtures, the lack of information about their type, and inconsistent research reports it has made difficult to compare obtained results and draw practical conclusions.

Another serious problem is that the testing methods for this kind of slurries are not standardised. The research on slurries is usually conducted using methods taken from the field of construction engineering. This means that the research on liquid slurries is supported with methods taken from drilling technology. In contrast, solid slurries are tested using methods taken from concrete engineering, soil mechanics, etc. It causes, that in spite of the hardening slurry cut-off walls are

designed as clay's cut-off walls, the designer often meets with difficulties caused by lack of necessary material parameters.

The paper shows the state of knowledge of the properties of hardening slurries and examples of the their applications in cut-off walls, based on literature and authors' research works.

The aim of the specification is not only to make design easier, but also an indication of the directions for further research in this kind of material.

2 State of knowledge in the field of hardening slurries

The state of knowledge of the properties of hardening slurries used as a material forming cut-off walls is represented in the table 1.

TYPE OF SLURRY	AUTHOR	MECHANICAL AND PHYSICAL PARAMETERS	COEFFICIENT OF PERMEABILITY and ADDITIONAL INFORMATION
1	2	3	4
cement - bentonite	Seitz, Haβ [8]	- compressive strength after 28 days of curing cycle Rc = 0.84 ÷ 1.1 [MPa]	$k = 10^{-9}$ [m/s] - linear dependence between density of the liquid slurry and density of hardened slurry after a year
cement - bentonite with admixture in form of waste sulphite liquor (water 1000 dm^3 portland cement 300 kg bentonite 200 kg admixture 2.5 kg)	Kledynski, Pisarczyk [4]	- slurry density $\rho = 1.26 \div 1.28$ [g/ cm^3] - stabilisation less then 2% ; - viscosity 50 ÷ 60 [s] ; - compressive strength $Rc_{(7)} = 0.24$ [MPa] $Rc_{(28)} = 0.33$ [MPa] $Rc_{(90)} = 0.37$ [MPa] - angle of repose after 7, 29, 35, 90, 20 days of curing cycle orresponding ϕ = 4.5, 4.5, 4.0, 12.0, 18.0 [°] - cohesion after 7, 29, 35, 90, 120 days of curing cycle corresponding c = 45,130,140, 200, 250 [kPa] - tensile strength during splitting after 7, 35, 90 days of curing cycle corresponding Rz= 0.074, 0.088, 0.102[MPa]	$k = 6.1 \cdot 10^{-9}$ [m/s]

1	2	3	4
bentonite-cement (portland or metallurgical) with the filler in form of: ground furnace slag, ash, cursed stone sand	Jefferis [2]		- usage of ash or metallurgical cement lengthens the setting time of the slurry; - usage of ash or metallurgical cement increases the viscosity of the slurry; - stability of slurry decreases when cement is partly substituted by a ground furnace slag; - cursed stone sand causes increase of strength parameters; - $k = 10^{-8} \div 10^{-11}$ [m/s] partly substitution of cement by furnace slag or usage of metallurgical cement decreases coefficient of permeability;
bentonite-cement (portland) with the filler in form of sand (water 1000 dm^3 bentonite 100-200 kg cement 250-350 kg sand 300-600 kg)	Kledynski [3]	- stabilisation 0÷18 % - compressive strength Rc = 0.24 ÷ 0.89 [MPa]	- hardening slurries are not freeze -resistant, - addition of sand does not significantly correct freeze resistance;
bentonite-cement (portland) with the filler in form of ground last furnace slag and admixture retarding setting	Potulski [6]	- compressive strength after 28 days curing cycle Rc = 0.42 ÷ 1.20 [MPa];	$k = 5 \cdot 10^{-8} \div 5 \cdot 10^{-9}$ [m/s]

1	2	3	4
bentonite-cement and bentonite-cement with admixture	Rafalski [7]	- compressive strength for CS/BS=0.1 ÷ 0.8 Rc= 0.02 ÷ 1.45 [MPa]; compressive strength increase mostly in 0-90 days curing cycle (CS -cement slurry, BS -bentonite slurry)	- the moisture of the medium has an influence on the strength parameters; on a medium with 95% moisture strength increases for 5 years. In dry medium shrinkage, and destruction of slurry takes place quickly; - addition of soda salt increases the compressive strength;
bentonite-ash (ash after brown coal combustion)	Rafalski [7]	- density of slurry ρ= 1.20 ÷ 1.40 [g/cm^3] - compressive strength after 28 days almost equal 0, after 60 days Rc= 0.12 ÷ 0.48 [MPa];	- relatively slow setting cycle; - reological properties may be regulated by a quantity of dispersing agent,
bentonite-calcareous	Rafalski [7]	- compressive strength after 60 days for CaS/BS = 0.3 ÷ 0.5 Rc = 0.24 ÷ 0.55 [MPa]; (CaS - calcareous slurry, BS -bentonite slurry)	- quite long setting time
bentonite-cement-ash	Rafalski [7]	- density of slurry ρ= 1.28 ÷ 1.29 [g/cm^3]; - compressive strength after 28 days Rc = 0.12 ÷ 0.7 [MPa];	
bentonite-ash	Jakubowska Kledynski [1]	- density of slurry ρ= 1.62 ÷ 1.70 [g/cm^3]; - compressive strength $Rc_{(14)}$= 0.29 ÷ 0.59 [MPa] $Rc_{(28)}$= 0.41 ÷ 0.66 [MPa] $Rc_{(90)}$= 0.43 ÷ 0.74 [MPa] - compressive strength increase mostly during 0-14 days; - cohesion after 65 days $c_{(65)}$= 55 ÷ 80 [kPa], cohesion decrease with increase of bentonite; - angle of repose after 65 days $\phi_{(65)}$= 22 ÷ 25 [°];	- viscosity increases with the increase of mixing time; - tensile strength during splitting is influenced by bentonite-cement ratio (the higher proportion of bentonite, the less tensile strength during splitting) k = $0.56 \cdot 10^{-7} \div 1.53 \cdot 10^{-7}$ [m/s]

1	2	3	4
bentonite-cement (Portland)- ash (water 1000 dm^3 bentonite 100-200 kg cement 100-200 kg ash 250-450 kg)	Kozyra Kledynski [5]	- density of slurry $\rho = 1.228 \div 1.395$ [g/cm^3]; - viscosity $V = 31.5 \div 49.7$ [s]; - stability $S = 0.2 \div 10.8$ [%]; - compressive strength $Rc(28) = 0.13 \div 0.48$ [MPa] $Rc(90) = 0.38 \div 2.11$ [MPa] - cohesion $c_{(15)} = 12.5 \div 100$ [kPa], $c_{(28)} = 47.5 \div 140$ [kPa], - angle of repose $\phi_{(15)} = 1.5 \div 11$[°], $\phi_{(28)} = 1.5 \div 11$[°]; - tensile strength during splitting $Rz_{(90)} = 0.084 \div 0.385$ [MPa];	- all of the components of slurry cause an increase of density; - the research confirmed dominating role of bentonite on viscosity and stability of slurries; - the exchange of part of the cement to ash, does not influence any of liquid slurries properties; - after the 28 days curing cycle, all of the slurries' components have an influence on the compressive strength. After the 90 days curing cycle, the influence of cement on these properties have been proven; - modifying the slurry by ash has a positive effect on solid slurry properties only within defined parameters. Both too little and too much ash results in the reduction of strength. - all of the slurries were soakable.

Table 1. Properties of hardening slurries used in cut-off walls

Until now, we have a lot of examples of the application of cement-bentonite and cement-bentonite with admixtures. Their properties meet the requirements which are establish for cut-off walls, such as watertightness, strength and durability.

Laboratory tests have shown however, that cement-bentonite-ash slurries, with determinate proportions of components also have suitable properties and can be accepted as a material forming cut-off walls. Additional advantages of using this kind of slurry are: costs reduction and creation of new methods of waste utilisation.

Research indicated also that bentonite-ash slurries (without cement) have significantly poorer parameters (i.e. lower watertightness) and can't be used as a material forming cut-off walls. They may be applied however as horizontal sealing of waste disposal sites, where the silting-up process takes place.

3 Examples of application of hardening slurries in Poland

Usage of hardening slurries in Poland has started a little later than in Western countries. Apart from well known foreign technologies (cut-off walls, prefabricate membrane walls), hardening slurries were used in new technologies, such as:

- foundations double T-bars lining, Berlin-type;
- filling of subsoil.

As the material forming cut-off walls during repairing works on earth dams, hardening slurry was used:

1. on Debe Dam on the Narew river, where a part of earth dam's cut-off wall has been repaired; cement-bentonite slurry with the admixture Rotarmix-1 (activator for bentonite and plasticizer) in quantity 1 - 3%; designed slurry has had the properties which are listed in table 2;
2. on Chancza Dam, where a cut-off wall in the earth dam embankment was executed; cement-bentonite slurry with the admixture Rotarmix-1; designed slurry has the properties shown in table 2.

	Kind of slurry	ρ [g/cm^3]	V [s]	S [%]	Rc(28) [MPa]	k10 [m/s]
Debe	cement-bentonite-Rotarmix-1	1.18 ÷ 1.40	30 ÷ 35	< 5%	0.3 ÷ 0.5	-
Chancza	cement-bentonite-Rotarmix-1	-	-	-	0.3 ÷ 0.5	10^{-8}

Table 2. Properties of hardening slurries used as a material forming cut-off walls during repairing works.

The hardening slurries were also used as a material forming cut-off walls sealing sediment traps in the following coal-mines:

1. "Morcinek" where the whole cut-off wall was made of modified cement-bentonite hardening slurry (as an admixture a composition of sodium carbonate and dibasic sodium phosphate was used); the designed slurry had the properties listen in the table 3;
2. "Ziemowit" where part of the cut-off wall was made of bentonite-metallurgical cement. The properties of a slurry are listen in the table 3;
   another part of cut-off wall was filled with clay clods. The cement-bentonite slurry was used as a filler to seal the clay clods.
3. "Ortowice-Kotlarnia", where the whole cut-wall was made of modified cement-bentonite slurry. The designed liquid slurry has the following properties:
   - viscosity $V \leq 100$ [s] (Marsh funnel),
   - density $\rho = 1.2 \div 1.4$ [g/cm^3];

The properties of hardened slurries (compressive strength, permeability) in mentioned above applications are listed in the table 3.

Location of the sediment trap	Kind of slurry	Rc(28) [MPa]	k10 [m/s]
coal mine Morcinek	modified bentonite-cement	0.1 ÷ 0.3	$< 5 \cdot 10^{-8}$
coal mine Ziemowit	bentonite-metallurgical cement	≥ 0.1	$< 5 \cdot 10^{-8}$
coal mine Ortowice-Kotlarnia	modified bentonite-cement	≥ 0.1	10^{-8}

Table 3. Properties of hardened slurries used as a material forming cut-off walls sealing sediment traps.

Hardening slurry has also been widely applied during the construction of Warsaw's underground. For example:

1. The foundation of double T-bars lining, Berlin-type. There was used the modified cement-bentonite slurry with an admixture of waste sulphite liquor. The composition of the slurry was as listed below:
   water 1000 dm^3, portland cement 350 [kg], bentonite 220 [kg], waste sulphite liquor 3.5 [kg];
   the slurry had following properties:
   - viscosity V = 35 ÷50 [s] (Marsh funnel),
   - density $\rho = 1.26 \div 1.30$ [g/cm^3],
   - stability S = 2 [%],
   - compressive strength $Rc_{28} = 0.25 \div 0.30$ [MPa],
2. Filling works in subsoil in order to obtain required properties (sealing, strength).

4 Final Remarks

Research performed so far and applications show that hardening slurry constitutes a suitable material for forming cut-off walls and it can also be used for other engineering works. A lot of the properties of a slurry have not been well recognised yet and further research has to be conducted in order to widen the application of this material .

5 Summary

The paper shows the state of knowledge of the properties of hardening slurries used as material forming cut-off walls, based on literature and author's research works. Some examples of applications in Poland are described.

Zusammenfassung

Der gegenwärtige Wissensstand auf dem Gebiet der Zusammensetzung von erhärtenden Suspensionen, die man als Material für Schlitzwände benutzt, wurde vorgestellt. Es wurde auch auf polnische Erfahrungen hingewiesen.

6 Literature

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