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Designing of Composition of Bentonite-Cement Slurry for Cut-Off Walls Constructed by the Monophase Method

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Abstract

To reduce the influence of mining waste on the ground and river water, two cut-offs have been completed in recent years in Poland. A bentonite cement slurry was applied to both cut-offs. The monophase cut-off construction process was possible by application of a sodium salt mix to modify the properties of the slurry. Structural and technological criteria are required to design the bentonite-cement slurry composition. It constitutes a mixture of bentonite slurry (BS), cement slurry (CS) and modifier (M).

The paper presents the results of investigations that performed to determine the procedure of designing the bentonite-cement slurry composition for cut-off walls. The relationship betweeen compressive strength R_S and CS/BS ratio of the bentonite-cement slurry specimens has been estimated. The procedure of designing the bentonite-cement slurry composition consists in determining of cement to bentonite slurry ratio, evaluation of bentonite content in the bentonite slurry, and cement in the cement slurry, as well as evaluation of modifier content.

1. Introduction

Watertight cut-off walls are not load-bearing structures but they prevent water movement in the ground. They can be particularly useful in decreasing the permeability of strata with high permeability coefficients (sand, gravel, etc.) overlying an impermeable stratum. Cut-off walls can be constructed like ordinary slurry trenches and backfilled. As backfill, different materials from plastic to rigid were used: soil-bentonite (Appolonia 1980), bituminous mixes (Boyes 1975), concrete (Xanthakos 1979) and others. Bentonite-cement backfills were widely applied to cut-off walls (Deere 1982, Kłosiński et al. 1987, Potulski 1992, Weiss et al. 1990). Publications on this subject are mainly devoted to presentation of construction methods. Despite many applications, there are only a few data in the literature concerning the designing of bentonite-cement slurry composition. Jefferis (1981) describes a triangular diagram of the bentonite-cement-water-system. In this, the principal regions are indicated: non-setting slurries, semi fluids, cut-off slurries, bleeding slurries and pastes or powders. According to the diagram, satisfactory bentonite-cement slurries for cut-offs including only bentonite, cement and water can be designed. This method of designing recommended for cut-offs has the following weaknesses:

- chemical additives which can influence the bentonite-cement slurry composition significantly are not considered,
- poor quality bentonites (e.g. sodium-calcium bentonites or bentonites including low clay particle content) cannot be included in practice and the quantities required are often much greater than those designed on the basis of the diagram.

Other publications describe the influence of particular components or applied additives on bentonite-cement slurry properties (Deere 1982, Portier 1984, Rafalski 1986, Valenta 1984).

In Poland two cut-off walls were completed during the period 1989 to 1992. The first enclosed the waste dump of the "Morcinek" coal mine near Cieszyn. It had a length of 2700 m, thickness of 0.4 m and maximum depth of 11 m and excluded the influence of waste on the river Olza. The second one surrounded the storage reservoir of highly saline water from the "Ziemowit" coal mine near Katowice. It had a length of 1047 m, thickness 0.6 m and maximum depth of 22 m.

Both cut-off walls were constructed by the monophase method using the bentonite-cement slurry modified with a sodium salt mix. The slurry was poured into a trench during the excavation process and protected the stability of the trench until the bottom was reached, then it was left undisturbed and gradually set. After setting, the bentonite-cement slurry formed the cut-off wall.

In this paper, the properties required of the bentonite-cement slurry for cut-off walls are analyzed and the results of tests performed to determine the procedure of designing the bentonite-cement slurry composition are presented. The influence of sodium salt mix on the optimum composition is also considered.

2. Properties Required of Bentonite-Cement Slurry

2.1. Structural Requirements

The slurry should form a durable, resistant and watertight cut-off wall in a trench. Thus, the following structural requirements of the slurry can be considered: strength, deformability, permeability and chemical resistance. Similar to soils stabilized by cement, the slurry has to harden and its strength can be defined by the minimum strength $R_{\min}$. As a cut-off wall has to be flexible to adapt itself to horizontal or vertical deformations of the ground Δx, Δy and Δz, the strength of the slurry cannot be too high and is defined as $R_{\max}$. Cut-off walls are loaded in practice by the ground including its deformations and by dead weights.

Between strength and respective deformation parameters of hardened slurry empirical dependencies are noticed (e.g. modulus of deformation E_0 and compressive strength R_S). Because of this, for purposes of designing the slurry composition, strength and deformability of the slurry can be represented only by one value of strength as a basic requirement, preferably the compressive strength R_S, thus $R_S \in (R_{S\min} \div R_{S\max})$.

Other structural properties of the slurry, i.e. permeability and chemical resistance, must comply with the requirements. The coefficient of permeability of bentonite-cement slurries varies only slightly. Chemical resistance of the slurry should be tested depending on the chemical composition of ground water where a cut-off is to be trenched. Both properties must be checked for suitability of the slurry.

The coefficient of permeability of the slurry should not be more than: $k_{10} < k_{10\max}$. Chemical resistance of the slurry can be represented by a loss in mass of Δm or by decrease in strength of ΔR_S and than: $\Delta m < \Delta m_{\max}$ or $\Delta R_S < \Delta R_{S\max}$.

2.2. Technological Requirements

Technological criteria are connected with the method of construction of the cut-off wall and concern the properties of the liquid slurry. The following properties have been selected as requirements concerning slurry suitable for trenching:

- density ρ,
- apparent viscosity η,
- gel strength τ_F,
- bleeding O,
- time of liquidity T_L,
- setting time T_S.

The density of slurry should be such as to assure stability of a trench during the process of its excavation: $\rho > \rho_{\min}$. In practice this criterion is formal as typical densities of bentonite-cement slurries are sufficiently high in comparison with those resulting from the trench stability analysis.

Capability of pumping through installations and displacing of the slurry in a trench can be assessed on the basis of its apparent viscosity, which should not be too high: $\eta < \eta_{\max}$. As a measure of thixotropic properties of the slurry, gel strength evaluates the possibility of creating gel structure that can carry cement particles and greater particles included in bentonite (silt and sand) to obtain non-sedimenting slurry. However, too high a gel strength of the slurry is disadvantageous as the process of excavation becomes difficult or impossible, thus: $\tau_F \in (\tau_{F\min} \div \tau_{F\max})$.

Homogeneity of the slurry is evaluated on the basis of bleeding. Stability of the slurry tested as the difference of density or strength at the bottom and top of the slurry column has also been considered but it proved that when bleeding is controlled then stability is also assured. Because of this, only bleeding of the slurry may be considered as: $O < O_{\max}$.

During the process of trenching, the bentonite-cement slurry should be sufficiently liquid. Coumoulos et al. (1983) proposed to determine the time of gelation of grouts with the aid of Casagrande apparatus. This method may be applied for bentonite-cement slurries. Apparent viscosity of the slurry is more helpful in testing its time of liquidity. The time of liquidity is evaluated when apparent viscosity of the slurry has reached its permissible value. The time of liquidity of the slurry must be appropriately long according to the method of trenching, thus: $T_L > T_{L\min}$.

Cut-off walls are most often constructed in sections. Time of setting of the slurry within a completed section should not be too long so as to not delay the process of trenching of the next section: $T_S < T_{S\max}$.

3. Concept of Designing Method

When designing the slurry compositions, it is convenient to consider the slurry as a mixture of bentonite slurry BS, cement slurry CS and modifying agent M with dispersing and retarding properties (Rafalski 1993). This enables proposing the following procedure of designing the bentonite-cement slurry composition:

- to determine the cement slurry and bentonite slurry ratio CS/BS on the basis of predicted compressive strength,
- to evaluate the cement content in the cement slurry C/W_C,
- to evaluate the bentonite content in the bentonite slurry B/W_B,
- to evaluate the modifier content in the bentonite-cement slurry M.

W_B and W_C are the water contents necessary to obtain the bentonite or cement slurry respectively. The total water content in the bentonite-cement slurry is $W = W_B + W_C$.

4. Experimental Section

4.1. Materials

The bentonite-cement slurries were prepared from the following components:

- water,
- bentonite Zębiec,
- Portland cement 35,
- modifiers: sodium bicarbonate and disodium phosphate mixed in weight proportions of from 0:2 to 2:0.

From the series of Zębiec bentonites that had been tested by Rafalski (1988), 3 bentonites were selected:

- bentonite 1 of $w_L = 161\%$,
- bentonite 2 of $w_L = 187\%$,
- bentonite 3 of $w_L = 211\%$.

4.2. Methods

- Compressive strength
  The bentonite-cement slurries were prepared in a rotating laboratory mixer with a capacity of 3 dm^3. Water and modifier were first mixed, then bentonite was added and mixing was commenced. Finally, cement was added and mixed. The bentonite-cement slurry specimens 8 cm in diam. and 8 cm high were kept for 28 days at a temperature of $18 \pm 2°\text{C}$ and relative humidity exceeding 95%. After 28 days static stress was applied and compressive strength measured.
- Apparent viscosity
  The slurry was sheared in a Fann rotational viscometer at shear rates: 1022, 511, 340.6, 170.3, 10.22 i 5.11 sec^{-1}. Apparent viscosity of the slurry was calculated at shear rate 1022 sec^{-1}.
- Gel strength
  Gel strength of the slurry was also tested in a Fann viscometer measuring the difference between shear stress obtained directly after stirring of the slurry and 10 min after stirring when the slurry was left undisturbed.
- Bleeding
  The slurry was poured into a graduated cylinder 1 dm^3 in volume and left undisturbed for 24 hours. After this time, bleeding of water in the slurry was measured.
- Density
  Density of the slurry was tested by its weighing in a calibrated vessel.
- Time of liquidity
  Apparent viscosity of the slurry was tested immediately it was prepared and after 2, 4, 8, 12, 16, 24, 32, 40, 48, 72 and 96 hours. Time of liquidity of the slurry was determined as the time necessary to obtain apparent viscosity $\eta = 20$ mPas.
- Time of setting
  Initial setting time of the slurry was tested by a Vicat apparatus after 12, 16, 24, 72, 96, 120 and 144 hours.

4.3. Research Programme

The research programme included four sequences.

- 28 days compressive strength of bentonite-cement slurry specimens of different compositions were tested. CS/BS ratio of the slurries was within the range of 0.1 to 0.8. In addition, every liquid slurry bleeding was tested directly after its preparation. This sequence consisted of 186 specimens and the same number of bleeding measurements.
- The series of 8 cement slurries with a C/W_C ratio of from 1.0 to 2.4 was tested to obtain the following properties: apparent viscosity, gel strength and bleeding.
- In comparison with traditional bentonite slurries applied for slurry walls, the bentonite-cement slurries have to include more bentonite to create a medium of proper gel strength for heavy cement particles. The purpose of this sequence was to determine the necessary increasing of bentonite content to obtain homogeneous bentonite-cement slurries. For every series, the CS/BS ratio was 0.3, the C/W_C ratio – 2.0 and B/W_B varied stepwise from 0.06 to 0.28 by 0.02. The modifier content was 1.2% of the total mass of other components. Bentonites 1, 2 and 3 were included. The apparent viscosity, gel strength and bleeding of the bentonite-cement slurries were measured.
- The series of bentonite-cement slurries of $CS/BS = 0.3$, $B/W_B = 0.24$, $C/W_C = 1.0$ (Portland cement 35) and modifier including sodium bicarbonate and disodium phosphate mix in the proportion 1:1 of content 0–3.0% was tested to find the influence of modifier on the slurries. Density, apparent viscosity, gel strength, bleeding, time of liquidity and time of setting of the bentonite-cement slurries were measured.

5. Test Results and Analysis

5.1. Dependence between Stress Strength R_S and CS/BS Ratio

Test results of 28 days compressive strengths of 186 bentonite-cement slurry specimens of different compositions are presented in Fig. 1. The linear regression line is also shown in Fig. 1, the correlation coefficient being $r = 0.82$ and standard error of estimate $SEE = 0.271$ as calculated for this function and test results. This means that the general relationship between CS/BS ratio and 28 days stress strength R_S of bentonite-cement slurry specimens has been confirmed. It is also noted that the test results are more scattered at higher CS/BS ratio. High scatter of test results is connected with bleeding of the slurries that were in the range of from 0 to 26% by volume. In case of high bleeding of the slurry, the concentration of solid components (bentonite and cement) grows in the slurry, then its compressive strength also becomes greater.

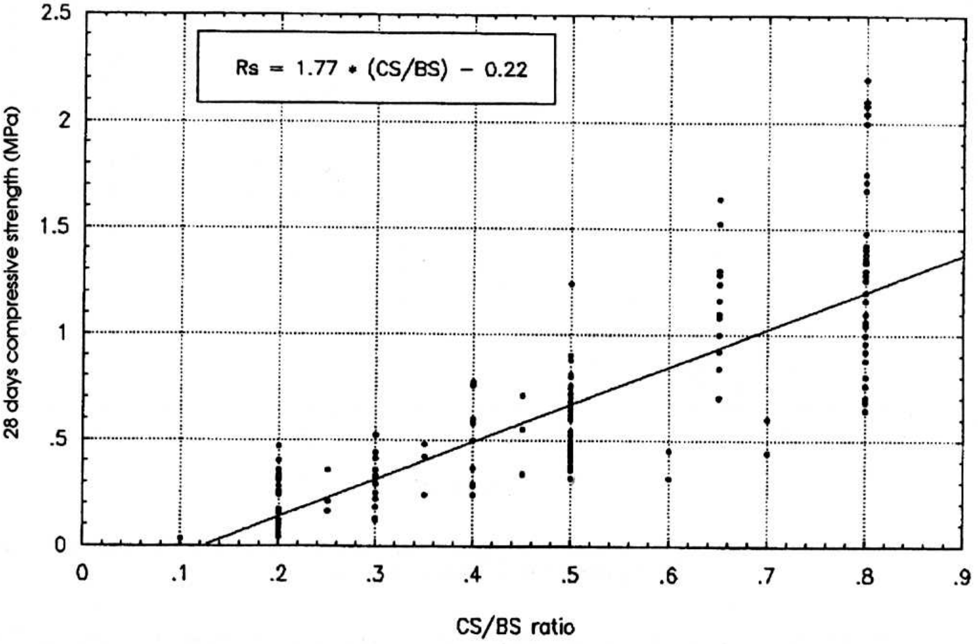

Fig. 1. Relationship between CS/BS ratio and compressive strength of bentonite cement-slurries of different bleeding (186 specimens)

This is more expressive for the slurry specimens of greater CS/BS ratio that can concentrate more cement after bleeding. Because of this high scatter, the relationship calculated for all specimens is not useful for predicting CS/BS ratio adequate to compressive strength R_S of bentonite-cement slurries. Of 186 test results, only those with bleeding of less than 5% by volume have been selected. Such criterion of bleeding is practically accepted for bentonite-cement slurries. In Fig. 2 these selected results are shown (48 data) and suitable linear approximation is also presented. In this case, coefficient of correlation $r = 0.94$ and standard error of estimate $SEE = 0.140$ have been calculated, thus correlation is much higher and scatter of test results is smaller. This confirms that the bleeding of the slurry has been the main factor of high scatter of test results presented in Fig. 1.

Generally, the function of relationship of 28 days stress strength R_S and CS/BS ratio of bentonite-cement slurry specimens can be described as:

$$R_S = A_1 \frac{CS}{BS} + A_2, \tag{1}$$

where A_1 and A_2 – constants dependent on the slurry components.

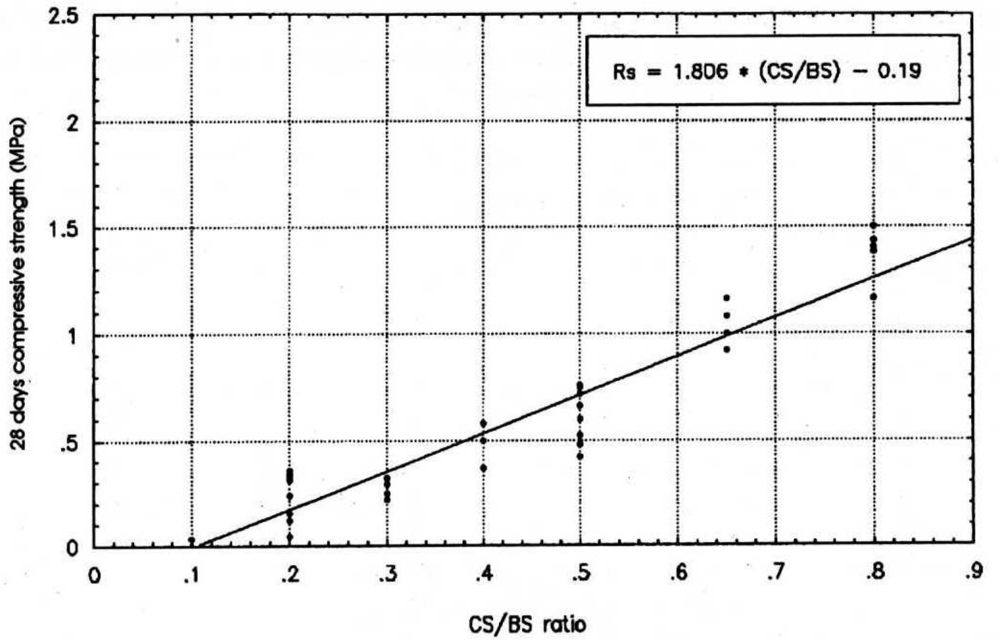

Fig. 2. Relationship between CS/BS ratio and compressive strength of bentonite cement-slurries of bleeding < 5% (48 specimens)

The relationship presented in Fig. 2 can be practically employed to predict $(CS/BS)_{PRED}$ ratio for given components when bleeding is less than 5% on the basis of predicted stress strength of the slurry R_{SPRED}, thus:

$$\left(\frac{CS}{BS}\right)_{PRED} \in \left(\frac{CS}{BS}\right)_{\min} \div \left(\frac{CS}{BS}\right)_{\max} = f_R(R_{SPRED} \in R_{\min\cdot} \div R_{\max}). \qquad (2)$$

5.2. Evaluation of C/W_C Ratio

Table 1 shows apparent viscosity, gel strength and bleeding of fresh Portland cement slurries with C/W_C ratio of from 1.0 to 2.4. For the designing procedure these properties represent liquidity of the cement slurry sufficiently. When concentration of cement in the slurry increases, apparent viscosity and gel strength grow and bleeding decreases noticeably. These relationships are well described by exponential functions (Table 1).

The suitable cement slurry should have liquid properties similar to properties of the bentonite-cement slurry as its component. Therefore, the criteria for bentonite-cement slurries may by used to determine the optimum C/W_C ratio (Fig. 3)

Table 1. Apparent viscosity, gel strength and bleeding of fresh Portland cement slurries of different C/W_C ratio

C/W_C ratio	Apparent viscosity η (mPas)	Gel strength τ_F (Pa)	Bleeding O (%)
1.0	4	2.4	30
1.2	5	3.4	18
1.4	7	4.8	10
1.6	10	5.8	7
1.8	13	7.7	4
2.0	18	9.1	2
2.2	28	12.5	1
2.4	41	17.7	1
Equation	$\eta = 0.69 \exp \times$ $\times (1.66\, C/W_C)$	$\tau_F = 0.66 \exp \times$ $\times (1.35\, C/W_C)$	$O = 510.53 \exp \times$ $\times (-2.77\, C/W_C)$

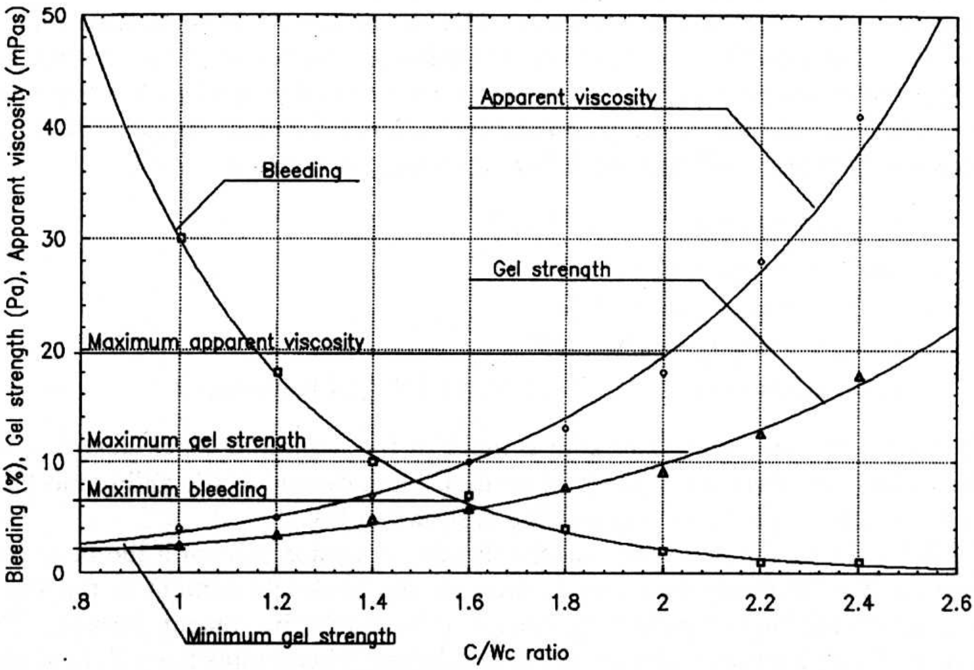

Fig. 3. Relationships between bleeding, gel strength, apparent viscosity and C/W_C ratio of cement slurries (Portland cement 35)

As relationships exists:

$$\eta_{CS} = f_{C1}\left(\frac{C}{W_C}\right) \quad \tau_{CS} = f_{C2}\left(\frac{C}{W_C}\right) \quad O_{CS} = f_{C3}\left(\frac{C}{W_C}\right) \tag{3}$$

thus:

$$\left(\frac{C}{W_C}\right)_{\min} = F_{C2}\ (\tau_{CS}) \tag{4}$$

and

$$\left(\frac{C}{W_C}\right)_{\max} = \text{minimum of } (F_{C1}(\eta_{CS});\ F_{C3}\ (O_{CS})\,, \tag{5}$$

$$\left(\frac{C}{W_C}\right)_{OPT} \in \left(\frac{C}{W_C}\right)_{\min} \div \left(\frac{C}{W_C}\right)_{\max}. \tag{6}$$

5.3. Evaluation of B/W_B Ratio

Publications on the use of bentonite slurries indicate that properties of bentonites are considered when the composition of the bentonite slurries is designed, e.g. Boyes (1975), Xanthakos (1979). Pulverized bentonites are mainly produced by drying and milling. Improvement of bentonite by separation of sand and silt particles is rarely applied due to costs and waste obtained which are very difficult to utilize. Thus, the quality of pulverized bentonite depends on properties and homogeneity of parent material. It was also confirmed that properties of a bentonite from the same deposit varied considerably. 10 samples of bentonite Zębiec tested between 1985 and 1987 had the following properties (Rafalski 1988):

- clay particles content f_i = 43–58%,
- plastic limit w_p = 31–42%,
- liquid limit w_L = 161–211%,
- plasticity index I_p = 129–174%,
- methylene blue test VB = 12.1–20.3 g/100 g of bentonite.

To predict the minimum bentonite content in the bentonite slurry designed for the traditional slurry walls, the best relationship between B/W_B and liquid limit of bentonite w_L has been selected and is shown in Fig. 4.

Referring to the bentonite-cement slurries, in comparison with the bentonite slurries, it is obviously necessary to increase the bentonite content in the slurry to create a medium of proper thixotropy to be loaded by cement particles. The test results of bentonite-cement slurries including 3 bentonites from Zębiec with liquid limit of 161%, 187% and 211%, are presented in Table 2. To select the slurries of liquidity necessary, the following criterions have been accepted:

- apparent viscosity $\eta_{\max} = 20$ mPas,

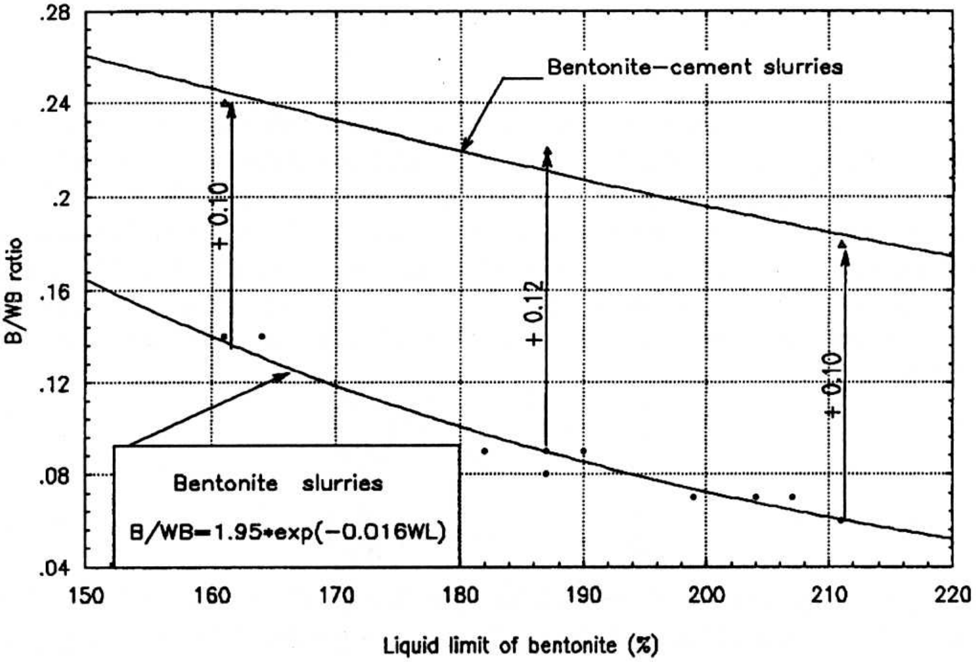

Fig. 4. Relationship of B/W_B ratio and liquid limit of bentonites for bentonite slurries and optimum B/W_B ratio for selected bentonite-cement slurries

Table 2. Apparent viscosity, gel strength and bleeding of bentonite-cement slurries of different B/W_B ratio

B/W_B ratio	Bentonite 1 ($W_L = 161\%$)			Bentonite 2 ($W_L = 187\%$)			Bentonite 3 ($W_L = 211\%$)		
	η (mPas)	τ_F (Pa)	O (%)	η (mPas)	τ_F (Pa)	O (%)	η (mPas)	τ_F (Pa)	O (%)
0.06	< 2.0	< 0.9	45	< 2.0	< 0, 9	48	< 2.0	< 0.9	36
0.08	< 2.0	< 0.9	42	< 2.0	< 0.9	44	< 2.0	< 0.9	28
0.10	< 2.0	< 0.9	36	< 2.0	< 0.9	38	< 2.0	< 0.9	21
0.12	< 2.0	< 0.9	31	< 2.0	< 0.9	28	< 2.0	< 0.9	15
0.14	2.5	< 0.9	17	3.0	< 0.9	18	3.0	0.9	12
0.16	2.5	< 0.9	15	3.0	1.4	10	4.0	1.4	7
0.18	3.5	0.9	12	4.5	1.4	9	**6.0**	**2.4**	**3**
0.20	4.0	1.4	8	5.5	1.9	8	8.0	2.9	1
0.22	6.0	1.9	6	**7.5**	**1.9**	**3**	24.0	7.6	0
0.24	**8.0**	**3.4**	**4**	12.5	3.4	1	46.0	8.2	0
0.26	18.0	7.2	2	19.5	4.5	0	84.0	12.7	0
0.28	42.0	12.4	1	38.0	4.8	0	n.o.	17.6	0

- gel strength $\tau_{F\,\min} = 1.4$ Pa and $\tau_{F\,\max} = 10.0$ Pa,
- bleeding $O_{\max} = 5\%$.

The properties of the slurries of various B/W_B ratio are also shown in Table 2 and presented graphically in Fig. 4. The results illustrate that the bentonite content in the bentonite-cement slurries tested should be increased by $\Delta(B/W_B) = 0.10 - 0.12$ as compared with adequate bentonite slurries. This increase is practically the same for the tested bentonites and the upper curve in Fig. 4 is displaced by a similar value from the lower curve. The bentonite content in the bentonite-cement slurry should by greater than the bentonite content in the bentonite slurry $(B/W_B)_{BS}$:

$$\frac{B}{W_B} = \left(\frac{B}{W_B}\right)_{BS} + \Delta\left(\frac{B}{W_B}\right) \tag{7}$$

or

$$\frac{B}{W_B} = f_L\,(w_L) + \Delta\left(\frac{B}{W_B}\right). \tag{8}$$

As only selected groups of bentonite-cement slurries of $CS/BS = 0.3$ have been tested, it is expected that $\Delta(B/W_B)$ will increase when the CS/BS ratio grows.

5.4. Evaluation of Modifier Content M

Modifying agents are necessary because bentonite-cement slurries obtained only by mixing water with bentonite and cement often do not indicate usually suitable technological properties. Many bentonites need a dispersing agent to achieve a thixotropic structure of the slurry. Additionally, when a modifier is absent, it is often observed that interparticle reaction between bentonite and cement particles in the slurry causes an increase in the apparent viscosity of the bentonite-cement slurry of $W = W_B + W_C$ as compared with the bentonite slurry of B/W_B ratio and the cement slurry of C/W_C ratio. To avoid such difficulties, chemical agents are applied as additional components of bentonite-cement slurries. The selected sodium salt composition includes: sodium bicarbonate and disodium phosphate. Sodium bicarbonate is known as a dispersing agent. Disodium phosphate has also dispersing properties but mainly retards time of liquidity of the slurry.

The test results of bentonite-cement slurry of $CS/BS = 0.3$, including a modifier M composed of a 1:1 sodium bicarbonate and disodium phosphate mixture, are presented graphically and approximated by curves in Figs. 5, 6, 7, 8, 9 and 10.

The modifier influences significantly the technological properties of the slurry with exception of its density. The slurry density has the same value irrespective of modifier content (Fig. 5). Apparent viscosity and gel strength of the slurry changes similarly (Fig. 6 and 7). At first, when the modifier content increases, apparent viscosity and gel strength grow. This is the result of the good dispersion of the slurry particles by sodium cations present in the modifier obtained by attraction

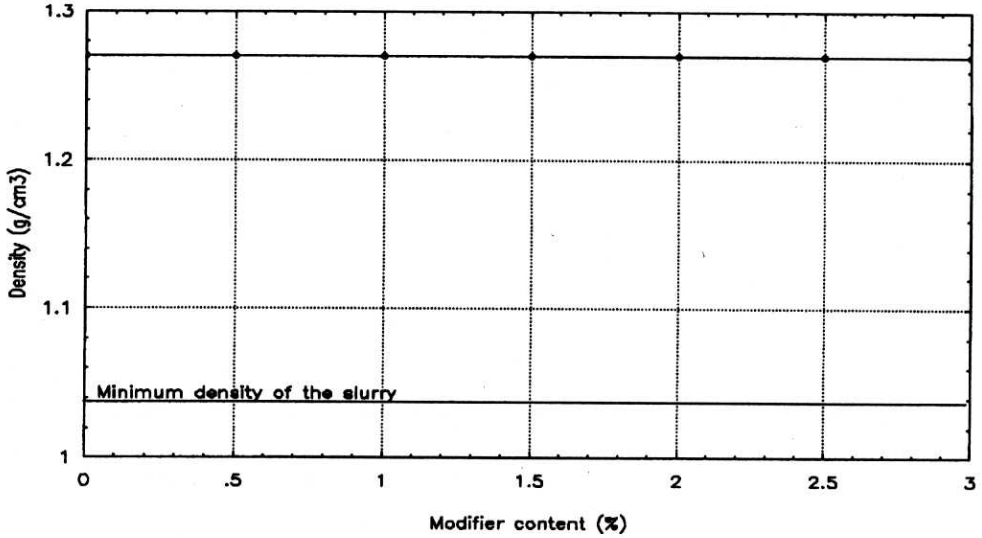

Fig. 5. Relationship of the density and modifier content of the bentonite-cement slurry

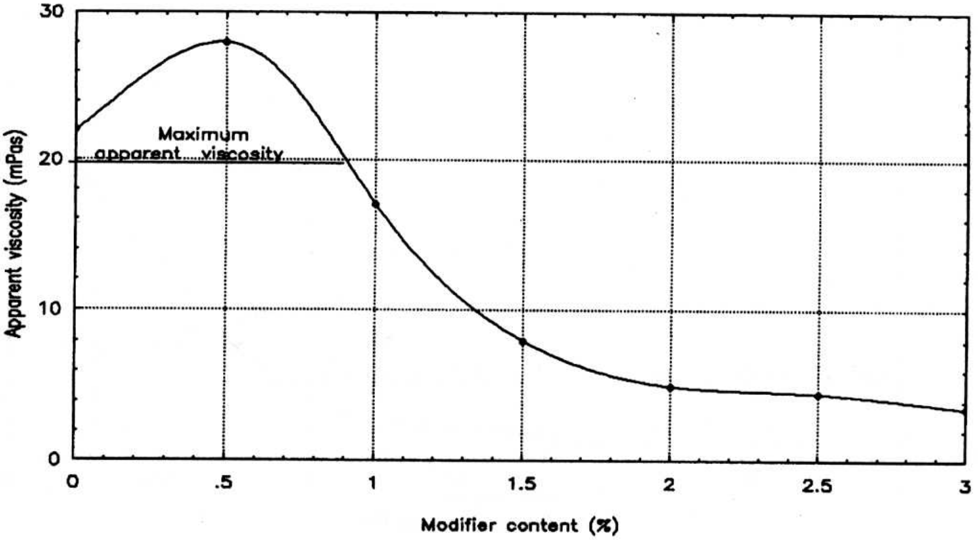

Fig. 6. Relationship of the apparent viscosity and modifier content of the bentonite-cement slurry

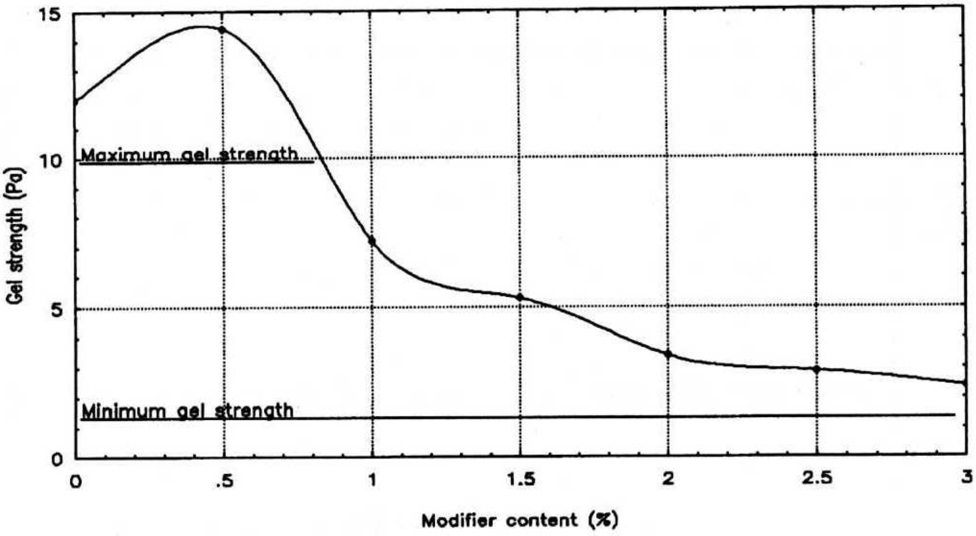

Fig. 7. Relationship of the gel strength and modifier content of the bentonite-cement slurry

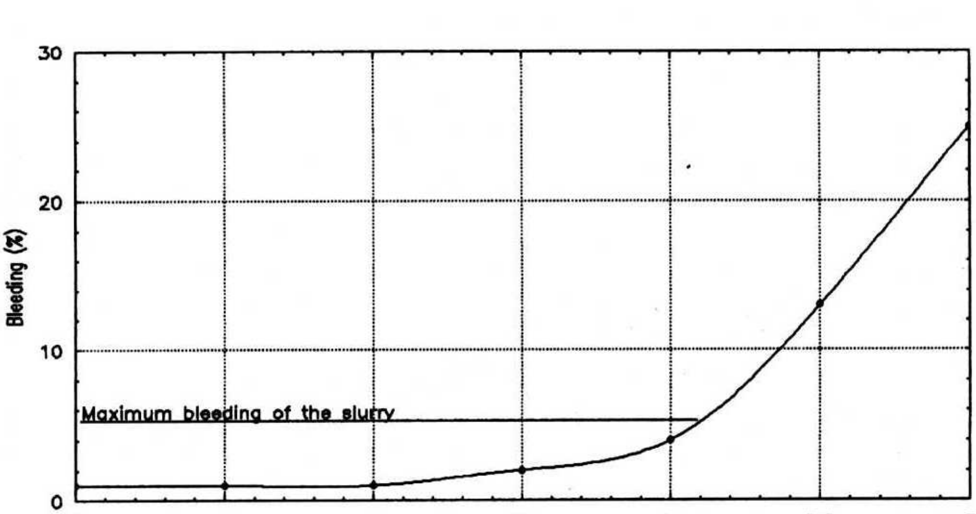

Fig. 8. Relationship of the bleeding and modifier content of the bentonite-cement slurry

of the positive edge charges and negative surface charges of bentonite particles. The significant sodium salt content also causes higher values of slurry bleeding. It is caused by reduced repulsion between bentonite flakes in the slurry.

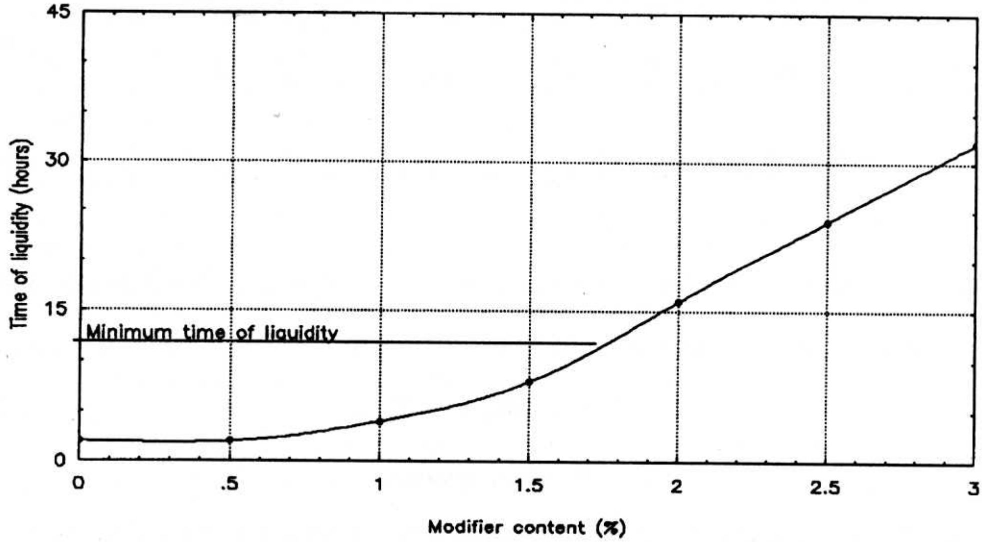

Fig. 9. Relationship of the time of liquidity and modifier content of the bentonite-cement slurry

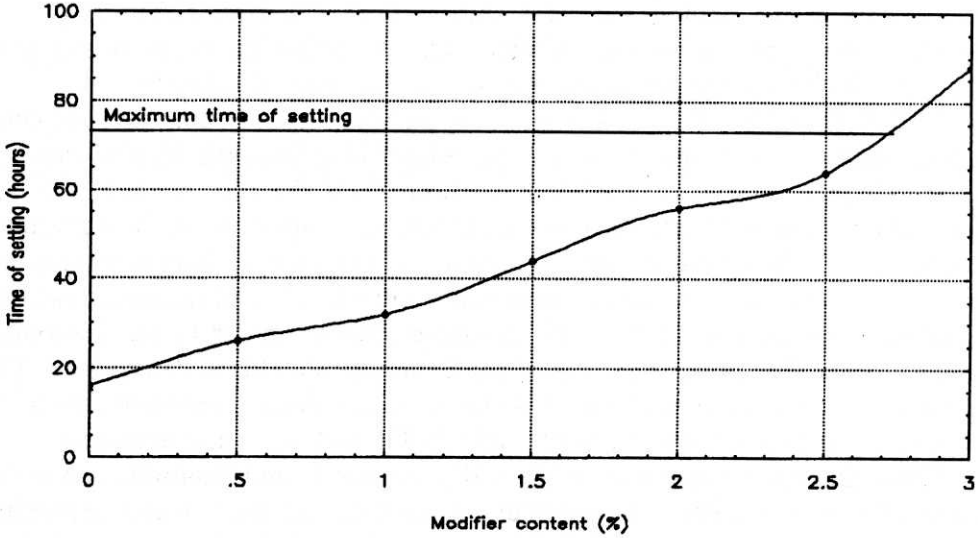

Fig. 10. Relationship of the time of setting and modifier content of the bentonite-cement slurry

Figs. 9 and 10 present the retarding influence of the modifier on time of liquidity and setting time of the slurry.

Evaluation of the modifier content has to be proceded by determination of the technological criteria: $\rho_{\min}$, $\eta_{\max}$, $\tau_{F\min}$, $\tau_{F\max}$, $O_{\max}$, $T_{L\max}$, $T_{S\max}$.

Existing are as relationships:

$$\begin{aligned} &\rho = f_{M1}\ (M); \quad \eta = f_{M2}\ (M); \quad \tau = f_{M3}\ (M); \\ &O = f_{M4}\ (M); \quad T_L = f_{M5}\ (M); \quad T_S = f_{M6}\ (M) \end{aligned} \tag{9}$$

thus:

$$M_{\min} = \text{maximum} \ \ \text{of}\,(F_{M2}\ (\eta_{\max});\ F_{M3}\ (\tau_{F\min});\ F_{M5}(T_{L\min})) \tag{10}$$

and

$$M_{\max} = \text{minimum of}\,(F_{M1}(\rho_{\min});\ F_{M3}(\tau_{F\max});\ F_{M4}(O_{\max});\ F_{M6}(T_{S\max})) \tag{11}$$

then the optimum modifier content is:

$$M_{OPT} \in (M_{\min} \div M_{\max})\,. \tag{12}$$

6. Conclusions

The bentonite-cement slurry may be considered to be a mixture of the bentonite slurry BS, the cement slurry CS and modifying agent M. Linear relationship betweeen compressive strength of bentonite-cement R_S and CS/BS 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. The following linear relationship has been found for the bentonite-cement slurries with bleeding less than 5%: $R_S = 1.806(CS/BS) - 0.19$. To design the optimum composition of the bentonite-cement slurry, it is necessary to assume compressive strength R_S and determine the CS/BS ratio using this linear function. Then, the cement slurry CS and the bentonite slurry BS are designed separately as components of the bentonite-cement slurry. The optimum cement content C of the cement slurry is determined from the relationships between cement-water ratio C/W_C and apparent viscosity η, gel strength τ_F, and bleeding O, assuming criteria similar to the bentonite-cement slurry. The liquid limit w_L of the bentonite should be determined. The optimum content of the bentonte B of the bentonite slurry is evaluated from the relationship between bentonite-water ratio B/W_B and w_L of the bentonite.

When the water content $W = W_B + W_C$, cement C and bentonite B are determined then the content of modifier M (sodium salt mix) of the bentonite-cement slurrry can be evaluated. Its content can be optimized from the relationships between M and density ρ, apparent viscosity η, gel strength τ_F, bleeding O, time of liquidity T_L and time of setting T_S assuming technological criteria of the bentonite-cement slurry.

References

Appolonia D. J. (1980): Soil-bentonite slurry trench cutoffs, *Journal of the Geotechnical Engineering Division,* Proceedings of the American Society of Civil Engineers, pp. 399–417.

Boyes R. G. H. (1975): *Structural and cut-off diaphragm walls,* Applied Science Publisher Ltd., London, pp. 118–134.

Coumoulos D. G., Koryalos T. P. (1983): Grout mixtures for ground improvement - laboratory testing and quality control, *Proceedings of the 11th Conference on Soil Mechanics and Foundation Engineering,* Helsinki, pp. 141–146.

Deere D. U. (1982): Cement-bentonite grouting for dams, *Proceedings of the Conference on Grouting in Geotechnical Engineering,* New Orleans, pp. 279–300.

Jefferis S. A. (1981): Bentonite cement slurries for hydraulic cut-offs, *Proceedings of the 10th International Conference on Soil Mechanics and Foundation Engineering,* Stockholm, pp. 435–440.

Kłosiński B., Rafalski L. (1987): Doświadczenia z zastosowań zawiesin twardniejących, *Materiały na VIII Krajową Konferencję Mechaniki Gruntów i Fundamentowania,* Wrocław, pp. 649–654.

Potulski B. C. (1992): Ścianka szczelinowa zapory ziemnej na rzece Harris (Australia). Projektowanie składu mieszanki zawiesinowej, *Inżynieria Morska i Geotechnika,* Vol. 1, pp. 36–40.

Portier J. L. (1984): Le comportment reel des coulis de bentonite-cement. Nouvelles applications, *Annales de L'Institute Technique du Batiment et des Travaux Publics,* Mars–20–34.

Rafalski L. (1986): Zawiesina twardniejąca z dodatkiem Rotarmix-1, *Prace IBDiM,* Vol. 2, pp. 116–117.

Rafalski L. (1988): Ustalanie składu zawiesiny betonitowej w zależności od jakości bentonitu, *Prace IBDiM,* Vol. 3, pp. 51–76.

Rafalski L. (1993): Projektowanie składu zawiesin twardniejących zastosowanych na budowie metra w Warszawie, *Materiały na X Krajową Konferencję Mechaniki Gruntów i Fundamentowania,* Warszawa, pp. 313–317.

Valenta D. (1984): Retardacia tuhnutia samotrdnucich suspenzii, *Inżenyrske Stavby,* Vol. 9, pp. 500–503.

Weiss W., Welzien K. (1990): Untersuchungen zur Weiterenwicklung selbsthärdener Suspensionen, *Bauplanung Bautechnik,* Vol. 3, pp. 108–111.

Xanthakos P. P. (1979): *Slurry walls,* Mc Graw-Hill Company, New York.