

Preparation for the Final Testing of the Sprayed Bentonite Sealing Layer of a Pond Dam

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Abstract. This paper presents research conducted on the development of a bentonite material suitable for the sealing of the dams of large ponds used for commercial fishing purposes. It is intended that the material will be applied using spray technology. The research was motivated by the large number of very old commercial fish ponds in the Czech Republic of which some are nearly a thousand years old. With the passage of time, leakage through the dams leads to the creation of caverns and preferential flow paths which may eventually result in a breach in the dam wall. An efficient technological approach to the sealing of these earth structures may, therefore, help to mitigate the risk of their failure and destruction. A potentially suitable material for this purpose has been researched and developed at the Czech Technical University and is now ready for the experimental testing phase involving the construction and study of a physical model of such a dam constructed according to the geometry of traditional commercial fish ponds.

1 Introduction

The landscape in the Czech Republic is unique with respect to the high incidence of commercial fish ponds. Their existence has exerted a strong influence on the formation of the landscape in many parts of the Czech Republic for a number of centuries. During the long history of these ponds, several ceased to exist for a variety of reasons which also contributed to the shaping of the landscape [1-4]. The risk of a dam breach is higher with respect to older ponds than for more recent structures due to their having been constructed employing different technology to that used today. The structure of dams made from earth may be negatively affected by the long-term flow of water through them. Dam breaches are very often very destructive events with serious consequences, and several such events have, historically, led to the loss of human life [5]. Although the most frequent reason for dam breaches remains the overreaching of the dam by excess water [6] and the consequent erosion of the downstream slope, slides of both the upstream and downstream slopes caused *inter alia* by internal dam wall failures [7] should not be neglected. Indeed, internal erosion constitutes one of the most important causes of these slides. Thus, it is important to be able to reduce the occurrence of seepage through such dams.

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Naturally, several approaches can be applied to the sealing of historical dam structures. However, sealing methods that exert the least effect on such dams in terms of maintaining their original, traditional character are usually preferred. The application of bentonite to the surface of the upstream slope is considered one such technique that fulfils the demand for maintaining the original appearance of the dam. A relatively thin bentonite layer is sufficient to limit leakage through the dams due to the very low hydraulic conductivity values of this material, thus having no effect on the historical shape of the dam structure. Nevertheless, it is necessary to note that the bentonite layer usually requires some level of protection from exterior disturbances of which several different types exist [8].

This paper describes the development of a bentonite material suitable for the spray technology to be applied for the repair of historical dams. The research involved the construction of a real-scale model (see Fig. 1) of a dam at the experimental centre of the Czech Technical University in Prague – Josef Underground Research Centre. The model was built following the technological methods employed in the past which differed from those employed today principally with respect to the construction of steeper slopes. A material with a relatively high permeability value was chosen for construction purposes so as to facilitate the proof of the comparatively good sealing properties of the tested bentonite materials. The experimental dam was equipped with a broad range of measurement equipment in order to capture the data necessary for the complex assessment of the impact of the applied bentonite layer. The measurements involved principally the monitoring of the water level in the reservoir and leakage through the dam accompanied by support measurements of the soil moisture content, ground pressure exerted in the dam foundations and temperature.



Fig. 1. View of the real-scale model of a dam as reconstructed from aerial imaging by UAS.

The most recent research focused on the preparation of the most suitable material for the given purpose and consisted of the testing of different mixtures and the subsequent laboratory analysis of their properties. Practical spray tests were also conducted.

The properties required of the sealing bentonite layer used in such dams are not specified in detail in the relevant literature. However, it is known that hydraulic conductivity and swelling pressure constitute particularly important parameters with respect to sealing, the required values of which for the testing of the sprayed sealing layer were set as follows:

- Hydraulic conductivity $k < 10^{-11}$ m/s,
- Swelling pressure $\sigma_{sw} > 0.5$ MPa

2 Technology for the application of bentonite for the sealing of pond dams

A range of different technologies exist suitable for the application of bentonite (or clay layers in general) for the sealing of dams, the most traditional of which consists of the application of clay as the upstream slope surface or shallow subsurface layer and which is applied with respect to both newly-built and existing dams. The application technology depends on many factors such as the slope or the required thickness of the layer; however, it generally consists of the spreading of the material on the pre-prepared surface of the dam and completion employing various techniques. Spreading can be performed either manually or via the use of machinery; however, the material must always be compacted using machines such as vibratory rammers or rollers. Such work may be limited significantly for example by the presence of trees on the upstream slope. In such cases, other methods may be preferable such as spray technology which has the advantages of being easily applied between obstacles such as trees and the fact that sprayed materials do not usually need to be further compacted.

Sprayed bentonite technology is based on that of the dry sprayed concrete process. The machine used for spraying (the spraying assembly) is composed of five parts, the first of which consists of the compressor, with respect to which the amount of air supplied to the transport pipe (power) makes up a crucial factor; moreover, the output rate was also found to influence the density of the material following injection. The main part of the spraying assembly consists of the SSB 14 DUO spraying machine (manufacturer Filamos Ltd., see Fig. 2b). The spraying mixture is poured into a hopper from which it feeds into a rotor which, in turn, serves to blend the mixture prior to its entering the compressed air stream (see Fig. 2a). The amount of material injected can be controlled by the rotor rotation speed. The other parts of the equipment consist of the transport hoses, two types of which are used for the application of the material. The first type is used to transport compressed air from the compressor to the SSB 14 DUO machine, while the second type is used to transport the compressed air mixture and the applied material from the machine to the spray nozzle. Via the careful selection of the diameter of the second hose, the resulting kinetic energy of the spray can be controlled and, provided the hose is of sufficient length, the uniform mixing of the feed material with the compressed air stream is ensured. The nozzle, which mixes water with a mixture of air and spray material, makes up the final component of the spray transport assembly. Due to initial problems with the clogging up of the nozzle, a new nozzle was designed at the CEG which eliminated problems associated with the mixing of the water and the spray material. The mixing water is conveyed to the nozzle by a hose fitted with a flowmeter which allows for the precise control of water inflow.

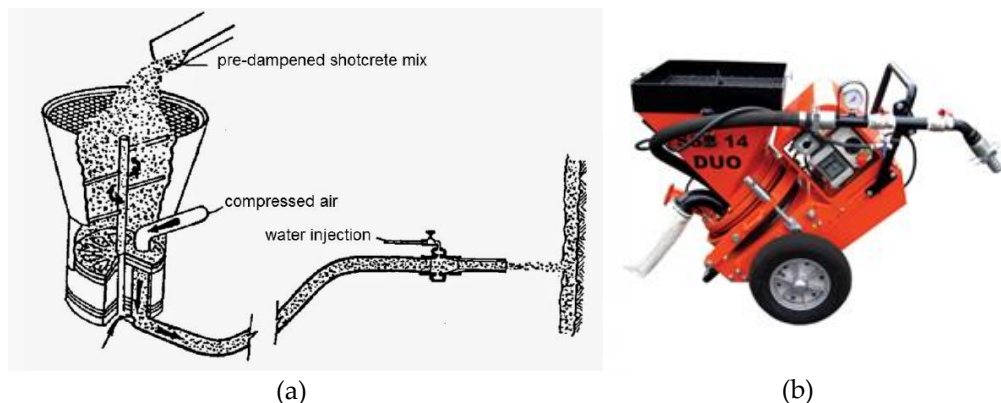


Fig. 2. Scheme of the dry mix spraying machine [9] (a) and the SSB 14 DUO spraying machine produced by Filamos Ltd. (b)

3 Developed material

Firstly, the type of powdered bentonite was selected, following which new granulated mixtures were prepared. All the granulated bentonites were developed in cooperation with the producers with respect to the adjustment of the mixtures. Hence, all the materials in question can be produced at the “real scale” if and when required (at a production rate of 1 tonne/hour).

3.1 Powdered bentonite

The Czech raw powdered Bentonite 75 (B75) was selected for the production of the granulated mixtures intended for spraying. B75 is a Czech calcium-magnesium bentonite with a montmorillonite content of around 75% [10] and is extracted from the Cerny vrch deposit in the Czech Republic. This material was chosen due to its availability and previous experience with its use. The other types of bentonites are less available which was the reason not to use them as the industrial production is expected in near future. Other available materials provided also worse results in mixing process which is quite difficult. The already dried, crushed and sieved bentonite was purchased from the KERAMOST company.

The basic geotechnical properties of B75 bentonite (average values obtained from the Centre of Experimental Geotechnics database and from [11-12]) are:

- Water content at the liquid limit 229%
- Water content at the plastic limit 65%
- Specific density 2.82 g/cm³
- Hydraulic conductivity at 1.5 g/cm³ 5.10⁻¹² m/s
- Swelling pressure at 1.5 g/m³ 3 MPa
- Swell index (volume of 2 g of B75 following swelling in water) 22 ml/2g

Figure 3 illustrates the sealing properties of B75 (hydraulic conductivity, swelling pressure), which have been proved to be highly dependent on the compaction level (dry density).

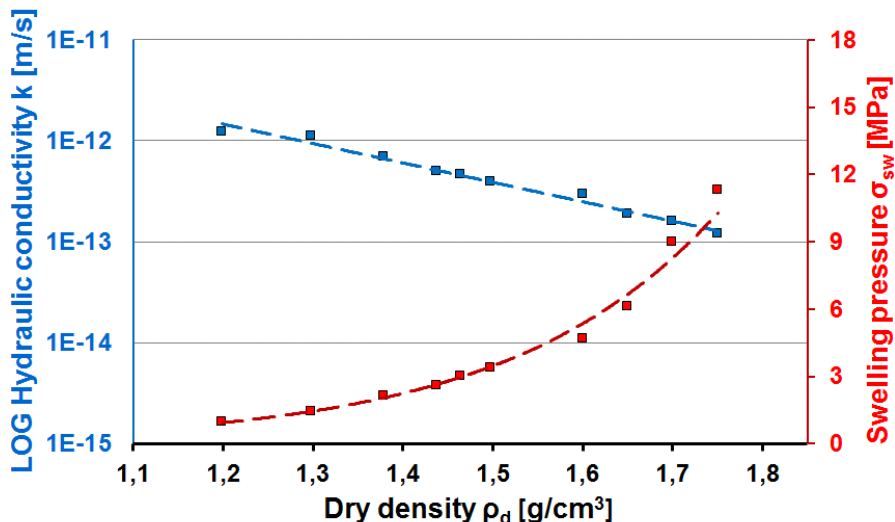


Fig. 3. Hydraulic conductivity and swelling pressure values for the selected B75 raw material [11].

3.2 Granulated bentonite

Granulated bentonite is produced via the compaction of the residue material employing roller press technology (see **Error! Reference source not found.** 4a). Following compression and drying, the material (labelled REC) is crushed. Prior to the crushing process, the pellets are plate-shaped with a length of up to 15 cm (see Fig. 4b). Following crushing, the bentonite plates are characterised by a maximum edge size of 5 cm. Industrial fractionation is achieved through sieving, via which it is possible to obtain a bentonite pulp with fragments in the range of, for example, from 0.8 to 2 mm up to in excess of 5 mm.

Several different mixtures were tested for research purposes, which resulted in the selection of B75 REC 0.8-2 mixture as exhibiting the ideal level of compaction following spraying. This mixture was then employed as the material to be used in the initial tests performed in order to determine the design of the new mixtures.

Since the bentonite mixtures obtained from the producer were “not ideal” for spray application purposes, it was deemed necessary to develop more suitable mixtures from the original material. The aim was to develop new mixtures which would comply with the Fullers equation for the “ideal” grain size distribution curve.

Consequently, two new mixtures (B75 REC MIX I (Fig. 4a) and B75 REC MIX II) were designed which met the Fullers grain size distribution requirements. Preparations were then made for the industrial production of the new mixtures in cooperation with the relevant research partners.

3.3 Material for final testing

B75 REC MIX I finally proved to exhibit the best match with the grain size distribution curve given by the Fullers equation. Thus, B75 REC MIX I was selected for final testing in the real-scale pond dam models. Fig. 4a shows B75 REC MIX I in the laboratory prior to spray testing and Fig. 4b shows the testing of the spraying of B75 REC MIX I onto the testing wall.



Fig. 4. B75 REC MIX I in the laboratory (left); picture of the spray testing of B75 REC MIX (right).

4 Results of the spray testing of B75 REC MIX I

The graphs in Fig. 5 show the results of the testing of the density (Fig 5a) and dry density (Fig 5b) of B75 REC MIX I following spray testing (Fig 5b) and depending on the water content of the material. The water content was regulated by means of a flowmeter. The results show that the level of compaction (dry density) of the sprayed material depends on its water content, a fact that is well known from the results of previous tests. The tests reported in this article were performed for the purpose of the evaluation of the impact of water inflow to the spray machine nozzle on the dry density of B 75 REC MIX I following spraying. The water content of the sprayed material was also studied. The impact of water inflow on the studied physical properties is shown in Fig 6.

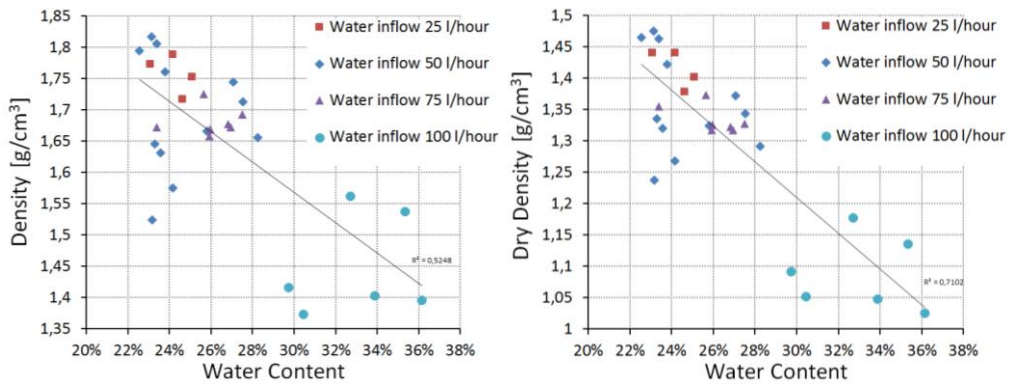


Fig.5. Graphs showing the results of the evaluation of density and dry density depending on the water content of the sprayed B75 REC MIX I with different water inflows to the nozzle.

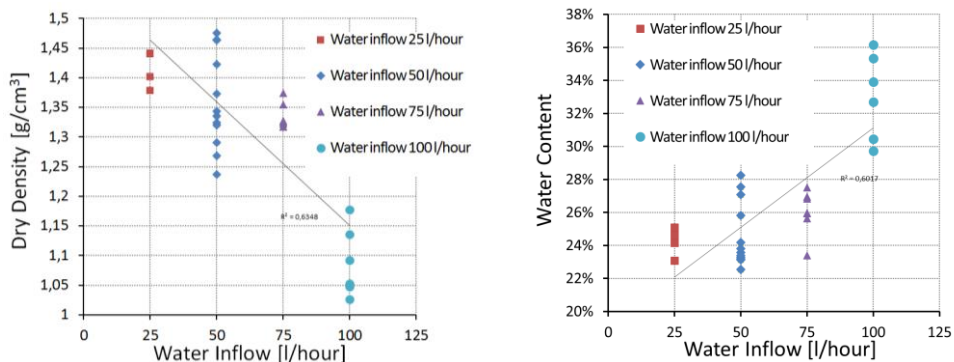


Fig. 6. Graphs showing the results of the evaluation of dry density and water content depending on the water inflow to the nozzle after the spraying of B75 REC MIX I.

5 Discussion

The results of the final spray test revealed that water inflow to the nozzle exerts an impact on the physical properties of the material. The values required by the project (hydraulic conductivity $k < 10^{-11}$ m/s and swelling pressure $\sigma_{sw} > 0.5$ MPa) were fulfilled since the dry density value did not fall below 1.2 g/cm³ for the water inflow values of 25 l/hour, 50 l/hour and 75 l/hour. The water inflow value of 100 l/hour was not applicable since a dry density level exists that generates sealing properties at the “minimal” level as given by the required values of the project.

In terms of technological feasibility, inflows of 50 l/hour and more (75 l/hour; 100 l/hour) exhibit a high efficiency rate since the rebound ratio (the material which does not “stick” to the testing wall) of the sprayed material and the level of dustiness are both relatively low when spraying outside (the water inflow rate of 25 l/hour leads to a high level of dustiness).

6 Conclusions

Recent results obtained from the project proved that the properties of the developed spray material are fit for the purpose. The material labelled B75 REC MIX I fulfilled the requirements set out at the beginning of the development of the ideal spray material regarding hydraulic conductivity and swelling pressure. Moreover, in terms of the technological aspect of the application of the developed material, the level of dustiness and the rebound ratio were found to be relatively low. The application of the material was rigorously tested as required with respect to both the use of the material in the pond dam model experiment and, subsequently, concerning commercial production.

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