THE USE OF POLYURETHANE IN COASTAL ENGINEERING MODELS

HENK JAN VERHAGEN (1)

(1) *Delft University of Technology, PO Box 5048, NL2600GA Delft, Netherlands, h.j.verhagen@tudelft.nl*

Abstract

In physical model tests there is often a need of preventing stones from moving. This can be achieved by gluing the stones. Applying PBA (Polyurethane Bonded Aggregates) guaranties no moving stones, a normal permeability and a transportable model.

Keywords: Physical model test; Epoxy resin, Polyurethane glue, PBA, Polyurethane bonded material

1. Introduction

In coastal engineering model tests often model consisting of loose materials (model rock) is used. When a Froude scale law can be applied, this usually results in quite satisfactory results. However, rebuilding the model is often problematic, because it is not possible to rebuild the model in exactly the same conditions. Also it is in some cases problematic to measure the permeability of a layer. This problem can be solved by gluing the stones together with a thin glue.

The volume of the glue should be negligible in relation to the volume of the voids between the stones (< 3% vol). Usually this can be achieved by using a polyurethane glue or an epoxy glue. In our lab we have some experience with the use of both products. A few years ago BASF has put on the market the product Elastocoast®, which is a polyurethane glue specially developed for the use in revetments. In this paper some examples of the use of polyurethane bonded aggregate (PBA) in coastal engineering models will be discussed.

2. Polyurethane and Epoxy glue

Stones can be glued together both with epoxy or with polyurethane glue. Because of their availability epoxy glues are the most common. Epoxy glue is a mixture of resin and harder, resulting in a strong, stiff bonding. To avoid bonding with the formwork, a special coating has to be placed on the formwork. Polyurethane glue is also a two component system (polyol and isocyanate). It has a comparable strength as epoxy, but is much more ductile and less brittle. The elastic properties of the material are much more favourable. Polyurethane does not bond to polyethylene, so covering formwork with simple polyethylene sheets prevent that the material is glued to the form. There are various types of polyurethane glue, but in this paper focus is glue specially developed to glue stones (polyurethane bonded aggregate, PBA).

3. Polyurethane bonded aggregate

The product Elastocoast as a polyurethane bonded aggregate has been developed by BASF for revetments (prototype scale application). This application will not be discussed here. For examples of PBA on revetments is referred to Bijlsma (2010).

Figure 1. Prototype PBA revetment (Bathpolder, the Netherlands)

In the research needed to investigate the behaviour of PBA on prototype scale also laboratory investigations were executed. During the setup of these tests, our laboratory staff realised that PBA also has specific advantages in physical coastal modelling. Based on this experience in our laboratory PBA is now frequently used as part of the various models. In this paper the focus is on application of PBA in coastal models. The advantage of using PBA is that is has the same hydraulic behaviour as loose riprap, but that it is not damaged and can be transported. The amount of glue in the total sample is negligible (less than 3% volume). Often in model experiments one needs to do several tests with exactly the same structure. However, rebuilding a loose rock riprap structure will never lead to exactly the same structure. Also the construction can be removed from the flume and placed elsewhere to investigate other aspects. This is relevant for example when investigation processes where the permeability is relevant.

The strength of PBA is considerable, and it has a good elasticity modulus (order 600 - 900 MPa) and a flexural strength of 2.5 – 3 MPa (Gu, 2007). This makes that models from PBA can be moved relatively easily without breaking.

4. Some examples of glued hydraulic coastal models

4.1 Permeability

In many wave-structure interaction processes the permeability plays an important role. For example Van de Meer has indicated that the permeability is a very essential parameter for the stability of riprap structures. However, he was not able to measure the real permeability of a structure. Measurement of the permeability of a single sloping layer in a composite construction is still impossible. The only way to measure the permeability of a layer is placing the layer into a test circuit and pump a given amount of water through the layer. The permeability can be computed from the measured discharge and the head differences on both sides of the sample. In such a test set-up one may keep the flow constant, so the Forchheimer relation reduces to:

$$\frac{1}{\rho g}\frac{\partial p}{\partial x} = i = au_f + bu_f\left|u_f\right| \tag{1}$$

In which:

$$a = \alpha\frac{\left(1-n\right)^2}{n^3}\frac{\nu}{gd_{50}^2} \tag{2}$$

$$b = \beta\frac{\left(1-n\right)}{n^3}\frac{1}{gd_{50}} \tag{3}$$

In such a test set-up the Forchheimer constants *a* en *b* can determined for the samples. However, from eq. 2 and 3 it is obvious that these constants strongly depend on the value of *n* (the porosity). When building a structure of loose material, this value varies therefore from construction to construction. Therefore the measured values for the constants *a* en *b* in a test set-up are always deviating from the values in the sloping structure.

By gluing the stones one gets a package of stones with a fixed permeability and porosity. Such a plate of PBA can be placed in a test section to measure the permeability. Subsequently one can place the same plate in a wave flume to do various investigations and one may determine for example wave damping as a function of the (real) permeability. As a first test six small samples have been prepared and the Forchheimer constants were determined. This resulted in the data from Table 1.

Figure 2: the six samples for the test

Table 1. Standard plates with tested Forchheimer constants

grading	d_{n50}	Layer thickness	*k*	α	β
8-11 mm	7 mm	39 mm	0.065	700	1.10
20-40 mm	20 mm	132 mm	0.131	1200	1.25

40-50 mm	39 mm	80 mm	0.154	1900	1.70
40–50 mm	39 mm	160 mm	0.214	1150	1.60
40-50 mm	39 mm	240 mm	0.213	1020	1.45

From these initial tests it is clear that simply using default values ($\alpha \approx 1000$ and $\beta \approx 1.1$) is not correct. For details is referred to Zeelenberg & Koote (2012).

A next step was to determine transmission and reflection by a breakwater with a given permeability. For this purpose a number of PBA-plates were produced and placed in our wave flume. The reason that we liked to have a vertical breakwater consisting of "loose" material is that for reflection and transmission of such a breakwater also theoretical solutions are available (Madsen and White, 1976). With PBA it is easy to construct such a vertical breakwater of loose material. Inside the "breakwater" a number of pressure gauges were included. Also this is an advantage of PBA. In real loose rock it is much more complicated to mound such pressure transducers on previously defined locations. The exact location is relevant, because the outcome of the physical model will be compared with the results of numerical calculations.

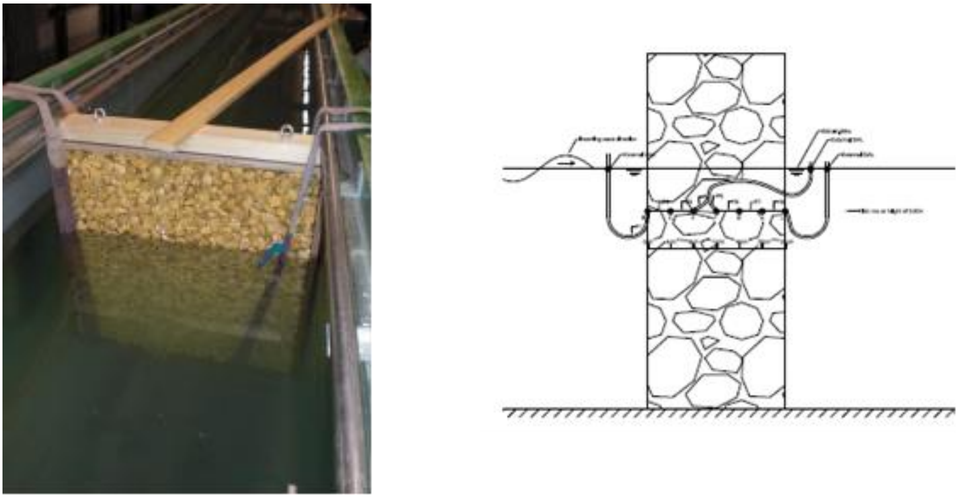

Figure 3. A piece of PBA in the flume with the location of pressure sensors (Mellink, 2012).

With this model accurate reflection and transmission data could be measured and compared with both the analytical as well as the numerical VOF model (Van den Bos & Verhagen, 2014).

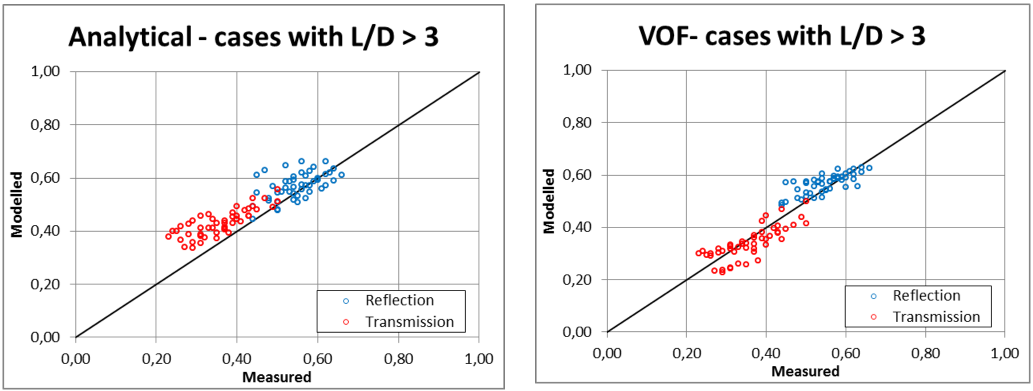

Figure 4. Results of the analytical and the numerical VOF model

4.2. Moving the model

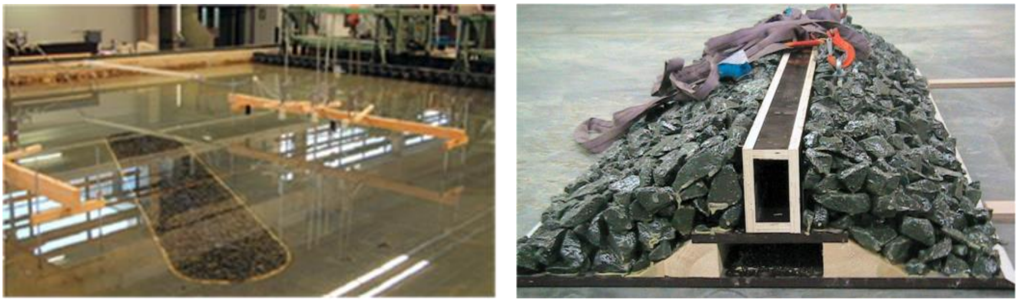

Figure 5. Movable models in a wave basin (models of Mulders and Vanlishout)

When testing models in a basin, waves should come from several directions. Often it is not possible to generate waves from any arbitrary direction, which make that you have to turn the model. PBA-models can be lifted easily and turned. The structure remains completely identical, so results can be compared easily. Both in the tests of Mulders (2010) as well as Vanlishout (2008), model sections with a size of approx.. 2.5 x 1 m could be hoisted and moved without any trouble.

4.3 Interface stability

In order to investigate the interface stability between cover layer and under layer, it is undesirable that the cover layer is moving. On the basis of full-scale tests with a PBA revetment (in the Grosser Wellenkanal in Hannover) Zoon (2010) was able to develop formulations of pressure gradients at such an interface layer. This work was the basis of follow

Figure 6. Flume and general set-up of the Van de Sande experiment

up work was done by Van de Sande (2012) on interface stability under flow conditions.

According to modern design rules for geometrically open filters, the filter thickness should be determined in such a way that both filter and sub layer should fail at the same moment. The experiment of Van de Sande was designed to verify this. He needed a filter layer which was partly erodible (to find the moment of failure of the filter) and partly not erodible (to measure the start of erosion of the sub layer). The erodible part and the non-erodible part needed to have the exact same permeability and porosity. Also the non-erodible part should be easy to remove in order to restore the underlying sand bed. This could be achieved by making four PBA plates of 394 x 500 mm. Figure 6 shows the detailed lay-out of his test.

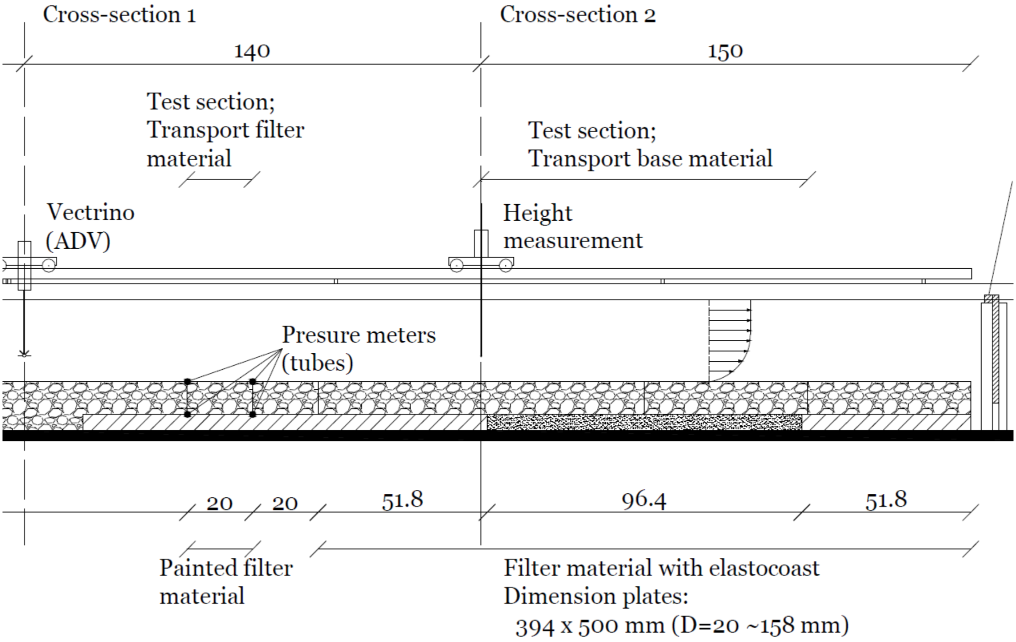

Figure 7. Location of the four Elastocoast plates in the Van de Sande Experiment

4.4 Stability of individual stones

In order to investigate the initiation of motion it is often required that one knows on beforehand which stone is going to move. This is important in order to focus measuring equipment on that specific stone. This can be achieved by either making a stone with the exact shape as a normal stone, but with a much lower density, or by gluing the surrounding stones together. The first option was applied in our lab by Hofland (2005) and by Hoan (2008). Hofland made a single tilting stone with a density of around 1800 kg/m^3. Hoan studied stone stability in decelerating flow. He made sets of several exact copies of natural stones from resin with a density of approx. 1350 kg/m^3.

Alternatively one can also glue the surroundings and make only one single stone movable. In recent work of Peters (2014) this has been done. Peters studied the stability of a single rock in a toe protection under influence of wave action. Therefore a glued toe was made with a limited loose stones. These are the coloured stones in Figure 7. Because the toe was glued, after movement of a single stone, that stone could be placed back in exactly the same way. So, the experiments are fully reproducible, and from multiple test good values of standard deviations could be obtained. Also in this case it is essential that the porosity and the position of the other stones is not changing during the experiment.

Figure 8: Glued breakwater to with six loose stones (Peters, 2014)

5. Importance of the model strength

For the above described tests of toe-stability instead of PBA an epoxy glue has been used. Because we had already some fear of breakage of the model, a reinforcement grid was added to the construction. See figure 9 (left). After completion of the tests, the toe was removed from the flume. It was not possible to do this without causing damage, see figure 9 (right). In this case it was no problem, because no further tests with this specific toe was foreseen, but it shows that the brittleness of epoxy glue is a problem. Also one may doubt if he reinforcement is not changing the hydraulic properties of the model.

6. Conclusions

Although developed for prototype application, PBA is a very versatile material for use in coastal laboratory research. Using PBA saves time in re-constructing model structures and allows repetitive measurements in "loose" materials. PBA has an advantage above epoxy, because it is more elastic and therefore less brittle. This is especially relevant when the model has to be moved regularly during the experiment.

Figure 9. Toe model glued with epoxy glue (Peters, 2014)

PBA has also a preference above "standard" polyurethane glues, because the composition of PBA (including the additives) has been made in such a way that the adhesion between the stones is at maximum, and still sufficient elasticity is provided for the structure.

Acknowledgments

The photographs in this paper have been provided by the authors of the papers referred to. Figure 1 has been reproduced with permission from BASF Netherlands.

References

Bijlsma, E. (2010), Polyurethane bonded aggregate revetments; design manual, Arcadis report 073962493, Amersfoort, The Netherlands

Gu, D. (2007) Some important mechanical properties of Elastocoast for safety investigation of dikes. Thesis, Delft University of Technology, Delft.

Hoan, N.T. (2008) Stone stability under non-uniform flow, PhD thesis, TU Delft, The Netherlands

Hofland, B. (2005) Rock and roll: turbulence-induced damage to granular bed protections, PhD thesis, TU Delft, The Netherlands

Madson, O.S., White, S.M. (1974) Reflection and transmission characteristics of porous rubble-mound breakwaters, USACE CERC Misc. report 76-6

Mellink, B.A. (2012) Numerical and experimental research of wave interaction with a porous breakwater, MSc thesis, TU Delft, The Netherlands

Mulders, P.H.M. (2010) Breakwaters under construction exposed to oblique waves, MSc thesis, TU Delft, The Netherlands

Peters, R. (2014, to be published) Stone stability in breakwater toes, MSc thesis, TU Delft, The Netherlands

Van de Sande, S.A.H. (2012) Stability of open filter structures, MSc thesis, TU Delft, The Netherlands

Vanlishout, V. (2008) Oblique wave transmission through rough impermeable rubble mound submerged breakwaters. MSc thesis, TU Delft, The Netherlands

Zeelenberg, W., Koote, M. (2012), The use of Elastocoast in breakwater research, BSc thesis, TU Delft, The Netherlands

Zoon, A. (2010). Cobble Sea defence: Hydraulic interface stability of sand underlying a single filter layer, MSc thesis, TU Delft, The Netherlands