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Towards a more rational approach for the design of cement-bentonite grouts

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Abstract

Cement-bentonite grouts are commonly used to seal boreholes containing different types of geotechnical instrumentation. The function and type of instrumentation and the surrounding ground conditions dictate the desired engineering properties of the grout, including strength, stiffness and permeability. Cement-bentonite grouts have been little studied, and there is not much guidance from which to determine the proportion of constituents (cement/bentonite and water) to obtain particular engineering properties in the final grout. This makes it desirable to try to mix or test grouts in the laboratory prior to deployment on site, but it can be difficult to know where to start. Further difficulties arise from the tendency to mix cement-bentonite grouts in small batches on site, where the water chemistry, the type and form of bentonite, and mixing apparatus may vary. The paper presents a brief summary of current understanding, and then looks at range of existing grout mixes and their engineering properties to propose an interaction diagram to try to suggest possible mixing and final set properties of grouts based on the proportion of constituents used (cement, bentonite and water). The diagram has some limitations, not least a lack of quantitative data to support some aspects, but the authors hope that it could form a rational basis that can be further developed.

Keywords: Grout, cement, bentonite, instrumentation, installation

1. Introduction

Cement-bentonite grouts are commonly used to seal boreholes containing different types of geotechnical instrumentation. The function and type of instrumentation and the surrounding ground conditions dictate the desired engineering properties of the grout, including its strength, stiffness and permeability. Compared with pure cement/water grouts, bentonite is added to reduce strength, brittleness, and stiffness for specific engineering applications. However, cement-bentonite grout is relatively little used compared with cement-only grouts and concretes and this makes their design, mixing and application of an area of continued development.

Sodium bentonite is most commonly used and contains mainly the clay minerals montmorillonite and kaolinite. Bentonite has a negative charge, and a large cation exchange capacity. When immersed in water, it undergoes intra-crystalline swelling followed by osmotic swelling that causes rapid uptake of large quantities of water, with the final extent of swelling dependent on the exchangeable cations (Durham, 1996). Water molecules link to the positively charged end of the clay platelets. When a solution of bentonite and water is mixed with positively charged cement particles, the clay and cement are attracted, and the system shows mutual flocculation. Free calcium ions in the cement have the effect of converting the sodium form of bentonite to its calcium form, which has the effect of reducing the clay swelling (Durham, 1996). As the cement in the grout cures it fixes the open structure formed by the bentonite, and the final set grout has a low density and high porosity.

There are several established grout mixes in the literature that appear to have been quite well used and tested, and are often recommended for applications where a stiff/strong or softer/less strong grout is required (see Mikkelsen, 2002). However, a wide range of grout mixes have been suggested for installation of instrumentation. This makes it difficult to work out what grout mix to use or how to adjust known mixes to achieve certain performance criteria both during preparation and in the final set grout. One approach is to mix and test a series of grouts in the laboratory to find one that is suitable, although this is potentially time consuming and cannot always be carried out. Cement-bentonite grouts are generally mixed on site in small quantities where it is sometimes difficult to control consistently material proportions and mixing. Preparation of grouts in the laboratory also needs to carefully replicate site conditions, as small variations in constituents (e.g. water chemistry) and mixing conditions can result in a grout on site that differs to that created in the laboratory.

This paper considers the relationships between the proportions of the constituents (cement/bentonite/water) and the resulting engineering properties using some limited data from the literature. An interaction diagram is suggested to summarise the existing understanding and guide the design of grout mixes in the laboratory and their potential adjustment during installation of instrumentation on site.

2. Engineering properties and performance of cement-bentonite grouts

The following considers the current understanding of how the constituents (cement/bentonite/water) influence a series of engineering properties of the wet and final cured grout. A more detailed discussion of some of these points is given by Mikkelsen (2002) and Contreras *et al* (2008). Some of the engineering properties will be revisited in Section 3 in relation to the analysed data set.

Mixability and separation. The prepared grout needs to be of a suitable consistency so that it can be pumped into a borehole. The proportions of constituents, the type and form of bentonite, the chemistry of the water used, duration and type of agitation/mixing, and the order in which components are mixed can all affect the consistency and viscosity of the fluid grout (Durham, 1996). If the grout is too thick (e.g. contains a higher proportion of solids to water) it will be difficult to pump and has the potential to block tremie pipes being used to place the grout into the bottom of a borehole. A thinner grout is easier to mix and pump, but if there is too much water in the mix, it will separate from the solids which sink to the base when the liquid grout is stood in a container for a short period; the same will happen to the grout placed within a borehole. The settled solids below the separated water will cure to form a grout, however the separation means that the set grout will contain less water and have a lower void ratio (= volume of voids/volume of solids) than mixed, and it is likely to be necessary to top-up the borehole at a later point to ensure the installation is sealed to the ground surface.

Strength. The strength of the grout mainly comes from the cement, and there appears to be a clear relationship between the water to cement ratio and the final compressive strength of the grout (Mikkelsen, 2002; Contreras *et al*, 2008). Some moderate strength is important to mimic the strength of the ground and for confinement of the instrumentation within the borehole, but for most applications high strengths are not needed.

Stiffness. For extensometer installations measuring vertical displacements along the axis of a borehole it is undesirable to have a grout significantly stiffer than the surrounding ground. Softer grouts with a higher water and bentonite content are typically used, although in practice most weaker grouts still tend to be stiffer than some soils such as normally consolidated clays (Mikkelsen, 2002). For installations measuring lateral displacements (i.e., an inclinometer), achieving a grout stiffness that exactly matches that of the ground is less important. It is however notable that there are few measurements of the compressibility or stiffness of cement-bentonite grouts on which to base mix design.

Permeability. The permeability of cement-bentonite grouts is important for sealing piezometers and sampling equipment into boreholes (Vaughan, 1969). Typical grout permeabilities lie in the range 1×10^{-7} to 1×10^{-9} m/s. Contreras *et al* (2008) show that so long as the final grout is within three orders of magnitude of the permeability of the ground, the error in the piezometer reading should be small. Cement bentonite grouts form a highly porous solid, with irregular arrangement of cemented particles, and Contreras *et al* (2008) show that the void ratio of the mix is the main influence on permeability.

Volume stability. Volume stability of the final grout can be important within the unsaturated soil zone above the natural water table. If the cured grout steadily dries because it is not immersed below groundwater, this may lead to shrinkage of the grout column and formation of cracks that may provide a preferential flow path or leave some installations inadequately confined. It is thus important for piezometer and inclinometer installations entirely or partly above the water table (e.g. Smethurst *et al*, 2015) that the grout is volume stable. A high bentonite/low cement content grout left to air dry in the laboratory will generally shrink and crack. Volume stability is provided by sufficient cement content forming a matrix that can resist shrinkage.

3. Analysis of grout mixes and properties

Mugo (2020) drew together a body of information on proposed and tested grout mixes, and considered a series of ways of trying to plot the mix proportions and resulting compressive strengths (for which there is a significant body of data). He found that plotting the ratios of water/cement (w/c) and bentonite/cement (b/c) against each other the most useful and intuitive: the ratios of water and bentonite to cement follows the quite common practice of stating the mix proportions by weight to ‘1’ part cement (e.g. Contreras *et al*, 2008), and allows common void ratios and densities to plot as straight lines. This paper follows the same approach. It is similar to that used by Durham (1996), who plotted bentonite as a % of the water content against water to cement ratio.

Mix - Water: Cement: Bentonite	W/C ratio	B/C ratio	Compressive strength (kPa)	Permeability (m/s)	Density (kg/m^3)	Void ratio	Reference and where known details of constituents
4.0 : 1 : 1.0	4.0	1.0		5.0 x 10^{-10}	1581.7	5.4	Vaughan (1974)
1.0 : 1 : 0.3	1.0	0.3			1309.2	7.8	All from Dunnicliff (1993): grout mixes suggested and tested by Fetzer (1982), Slope indicator (1982), Easton (1984) and Minnitti (1985).
0.5 : 1 : 0.0	0.5	0.0			2414.5	1.6	
2.5 : 1 : 0.3	2.5	0.3	280		1671.6	5.6	
6.6 : 1 : 0.4	6.6	0.4	25		1335.8	13.5	
6.6 : 1 : 0.4	6.6	0.4	15		1335.8	13.5	
12.5 : 1 : 1.38	12.5	1.38	20		1268.4	13.8	
1.3 : 1 : 0.03	1.3	0.03			1960.8	3.8	McKenna (1995)
1.0 : 1 : 0.06	1.0	0.06	13100		2082.7	2.9	Durham (1996) Tables 3.5 and 3.6 which are reproduced from Laporte Industries. Bentonite was Fulbent 570.
2.0 : 1 : 0.12	2.0	0.12	2140		1740.6	5.4	
5.0 : 1 : 0.3	5.0	0.3	110		1405.1	11.2	
0.8 : 1 : 0.04	0.8	0.04	22890		2229.6	2.3	Durham (1996) Table 3.8, which is reproduced from Steetly Minerals. Bentonite was Birkbent CE. The mixes from Laporte Industries above and Streetly Minerals are a broad range of tested mixes, for a range of potential applications.
0.8 : 1 : 0.05	0.8	0.05	23860		2230.5	2.2	
1.0 : 1 : 0.05	1.0	0.05	12760		2081.5	3.0	
1.0 : 1 : 0.07	1.0	0.07	12430		2084.0	2.9	
2.0 : 1 : 0.1	2.0	0.1	1480		1736.8	5.6	
2.0 : 1 : 0.14	2.0	0.14	1630		1744.5	5.3	
3.0 : 1 : 0.15	3.0	0.15	460		1562.7	7.9	
3.0 : 1 : 0.21	3.0	0.21	790		1573.8	7.4	
4.0 : 1 : 0.2	4.0	0.2	340		1465.0	9.9	
4.0 : 1 : 0.28	4.0	0.28	340		1478.3	9.2	
5.0 : 1 : 0.25	5.0	0.25	110		1397.6	11.8	
5.0 : 1 : 0.35	5.0	0.35	230		1412.4	10.7	
4.0 : 1 : 0.2	4.0	0.2	57		1465.0	9.9	Durham (1996) Tables 5.1 and 6.1, which are mixes designed and tested by Durham, for use in geotechnical instrumentation applications. The constituents were Ordinary Portland Cement and Brebent sodium montmorillonite from Laporte Industries. The grouts were tested using a shear vane apparatus.
4.0 : 1 : 0.4	4.0	0.4	99.6		1497.4	8.2	
4.0 : 1 : 0.6	4.0	0.6	164.6		1527.5	7.0	
4.0 : 1 : 0.8	4.0	0.8	179.6		1555.5	6.1	
6.0 : 1 : 0.3	6.0	0.3	29.4		1349.9	13.5	
6.0 : 1 : 0.6	6.0	0.6	49		1389.0	10.4	
6.0 : 1 : 0.9	6.0	0.9	67		1425.1	8.5	
6.0 : 1 : 1.2	6.0	1.2	90		1458.6	7.2	
8.0 : 1 : 0.4	8.0	0.4	8.6		1285.7	16.4	
8.0 : 1 : 0.8	8.0	0.8	29.6		1328.8	12.1	
8.0 : 1 : 1.2	8.0	1.2	41.6		1368.4	9.6	
8.0 : 1 : 1.6	8.0	1.6	62.6		1405.1	8.0	
10.0 : 1 : 0.5	10.0	0.5	7		1245.2	18.8	
10.0 : 1 : 1.0	10.0	1.0	20.4		1290.8	13.4	
10.0 : 1 : 1.5	10.0	1.5	36.2		1332.8	10.4	
10.0 : 1 : 2.0	10.0	2.0	44.6		1371.5	8.5	
12.0 : 1 : 0.6	12.0	0.6	5.4		1216.9	20.9	
12.0 : 1 : 1.2	12.0	1.2	19		1264.3	14.5	
12.0 : 1 : 1.8	12.0	1.8	30.2		1307.9	11.1	
12.0 : 1 : 2.41	12.0	2.41	42.6		1348.1	8.9	
2.5 : 1 : 0.3	2.5	0.3	340		1671.6	5.6	Mikkelsen (2002)
6.6 : 1 : 0.4	6.6	0.4	28		1335.8	13.5	
2.5 : 1 : 0.35	2.5	0.35	600	2.0 x 10^{-08}	1680.3	5.4	Contreras *et al* (2008). Cement: Ordinary Portland Cement. The first four mixes contained Baroid Quickgel bentonite, and the final two Baroid Aquagel Gold Seal.
6.6 : 1 : 0.4	6.6	0.4	90	7.0 x 10^{-08}	1337.9	13.4	
4.0 : 1 : 0.67	4.0	0.67	220	3.2 x 10^{-08}	1538.5	6.6	
2.0 : 1 : 0.36	2.0	0.36	1720	1.2 x 10^{-09}	1783.5	4.2	
2.5 : 1 : 0.41	2.5	0.41	840	6.0 x 10^{-09}	1692.2	5.1	
6.6 : 1 : 0.19	6.6	1.19	120	5.2 x 10^{-08}	1424.1	8.0	
3.6 : 1 : 2.0	3.6	2.0			1731.8	3.1	MGS (2019) proprietary mix, containing Ordinary Portland Cement and sodium carbonate activated bentonite.
4.2 : 1 : 2.0	4.2	2.0			1670.8	3.6	
4.8 : 1 : 2.0	4.8	2.0			1619.2	4.1	
6.0 : 1 : 2.0	6.0	2.0			1536.7	5.1	

Table 1: Cement-bentonite grout mixes proposed in the literature. Proportions are by weight.

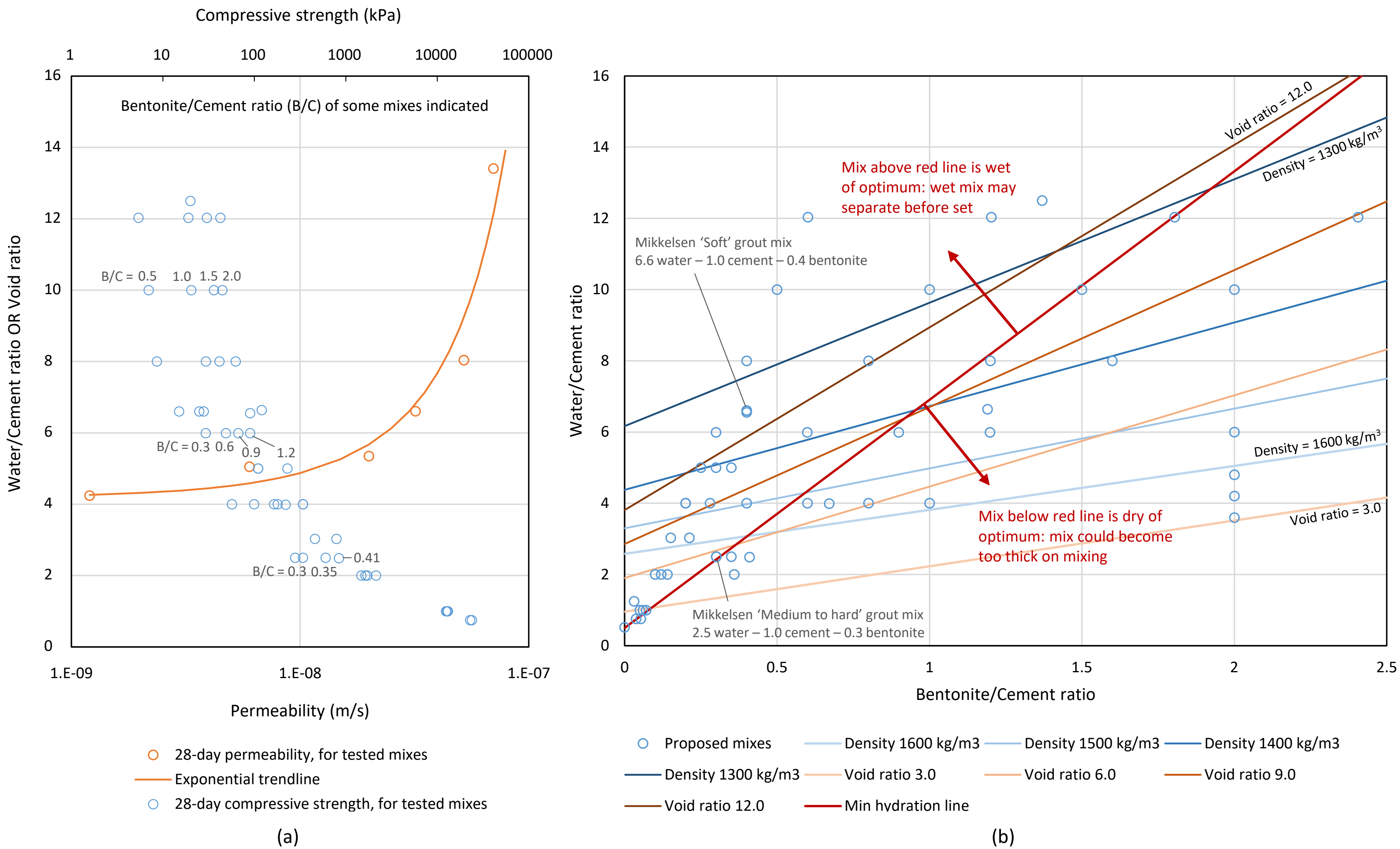

Figure 1: Grout mixes given in the literature plotted as (a) 28-day compressive strength against water/cement ratio (blue) and 28-day permeability against void ratio (orange – from Contreras *et al*, 2008 for the middle confining stress level applied); and (b) bentonite/cement ratio against water/cement ratio.

Table 1 shows the cement-bentonite grout mixes found by Mugo (2020) and supplemented by further grout mixes given in Durham (1996). The table shows that there is a wide range of mixes defined by the proportion of constituents, and that most mixes were tested for compressive strength, and a small number for permeability. The grout density stated is based on assumed densities for cement, bentonite and water of 3150 kg/m^3, 2340 kg/m^3 (which assumes that the bentonite has 10% moisture content by weight when mixed) and 1000 kg/m^3. If the details of the constituents are known these are stated, however, many details of preparation, mixing and testing of the grouts are unknown, and there is likely to be considerable variability between studies. A key uncertainty – as it is rarely stated – is whether any separation occurs before set, as this would mean that the final grout obtained and tested has a lower water content and void ratio, and greater density, than as mixed.

There is a generally well-established relationship between the water/cement ratio and the compressive strength of the final grout; this is plotted in Figure 1(a) for the assembled grout mixes for which 28-day compressive strengths (or shear strengths) were tested. As observed by others, the main control on compressive strength is the water/cement ratio; when this is low the grout exhibits concrete like strengths. The bentonite to cement ratio is also labelled onto the figure for some mixes, and this shows that for the same water/cement ratio a greater bentonite content also slightly increases the compressive strength, presumably because the lower void ratio and greater density allow the solids component to cement to form a stronger matrix. Figure 1 (a) also shows the relationship between 28-day grout permeability and void ratio, using data from Contreras *et al* (2008). Note that there is much other data available on both compressive strength and permeability that is not presented here, particularly for different times from casting (e.g. 7 days, as well as other durations).

The mix proportions from Table 1 are plotted in Figure 1(b) as the ratios of water/cement and bentonite/cement by weight, as proposed earlier. The well-known Mikkelsen (2002) grouts are specifically labelled. Onto the same plot, a series of further lines have been added:

- In orange, lines of constant mix density, based on the densities stated for the constituents above.
- In blue, lines of constant mix void ratio (= volume of voids /volume of solids) assuming that the fluid/set grouts are completely water saturated (i.e. there is no trapped air) so that the void between the solid particles is completely occupied by water. These are also based on the material densities stated above.
- In red, running diagonally upward across the plot, a line representing the minimum mass of water required to fully hydrate both the cement and the bentonite, termed here the 'minimum hydration line'. This is based on a w/c ratio of 0.38 required for complete hydration of ordinary Portland cement (Powers and Brownyard, 1948; Taylor, 1990), and a w/b ratio of 6.4 required for complete hydration of sodium bentonite (based on the average of a number of sources, including manufacturers data sheets and information in Gurner, 1978). Note that this ignores any chemical interaction between the cement and bentonite which may reduce the amount of water required to hydrate the bentonite.

Figure 1(b) shows that higher w/c ratios produce a fluid cement-bentonite grout mix of lower density and higher void ratio, as might be expected with increasing water content. The 'minimum hydration line' runs diagonally upwards across the plot spanning most of the plotted lines for density and void ratio; the increasing quantity of bentonite requires the addition of a lot of water for hydration. Many of the suggested grout mixes from the literature sit above the 'minimum hydration line' indicated, although a few are below it. Note that the exact location of the 'minimum hydration line' is a little uncertain, since the amount of water required to hydrate the solids can depend on the types of cement and bentonite (here assuming ordinary Portland cement and sodium bentonite), the water chemistry, and chemical interaction between the cement and bentonite. However, mixes sitting significantly above the line plotted should contain more water than is required to hydrate the cement and bentonite, and these mixes may well separate on standing for some time. Mixes a little below the red line may be ok, but if a long way below the red line they may not contain enough water to hydrate the cement and bentonite. This may work if the constituents are mixed and placed into the borehole quickly, but prolonged mixing/agitation may cause the mix to thicken too far for it to be pumped or tremmied.

4. How the chart can be used in design

Given the limitations of Figure 1(b) noted above, it is always advisable to carry out a trial mix of possible grouts. Figure 2 shows how the chart may be used to think about adjusting an initial grout mix to get the correct engineering behaviour. Above the 'minimum hydration line', grouts may separate. Once water has separated out and the hydrated solids have cured, the set grout obtained is likely to be that by moving downward vertically towards the 'minimum hydration line' (following path 1). It may be desirable not to mix the grout with excess water that will separate, unless that makes it too viscous to be pumped etc. The potential actions are to reduce the water content (path 1), increase the amount of bentonite to again move closer to the minimum hydration line (path 2), or a combination of the two (path 3). Path 2 generally follows the advice by Mikkelsen (2002) to add cement first and then adjust the bentonite content so that a pumpable mix with the consistency of single cream is obtained, likely indicating that there is not excess water beyond that required to hydrate the solids. The plot of compressive strength and permeability (Figure 1a) and the lines of density and void ratio on the main chart (Figures 1b and 2), indicate what will happen to the grout if the above paths are followed. In this case, Path 1 will give a greater compressive strength and likely stiffness, and lower void ratio and thus permeability, than following Path 2, which will give similar but with less effect (e.g. the bentonite content will increase the compressive strength, but less so than a reduction in the water/cement ratio).

The chart has recently been used successfully by the authors to help define and adjust a grout mix for an installation within a domestic waste landfill. A 20 m long, 250 mm diameter borehole was drilled at an inclined angle of 45° and lined with a flexible plastic sleave fitted with lysimeter vacuum water samplers along its length. To achieve and maintain good contact between the vacuum samplers and waste, the flexible sleave was filled with a cement-bentonite grout mix. The desired set properties of the grout were to have sufficient strength to hold the borehole open, not shrink on curing, yet remain plastic to accommodate anticipated differential settlement in the landfill. The grout also needed to be sufficiently fluid to pump through a narrow tremmie pipe. Figure 1(b) was used to adjust a starting mix until the optimal properties were obtained, confirmed by laboratory tests. On installation, the properties of the installed grout did differ a little from those in the laboratory tests, possibly due to differences in water chemistry and the method of mixing, although the overall desired fluid and set properties were achieved.

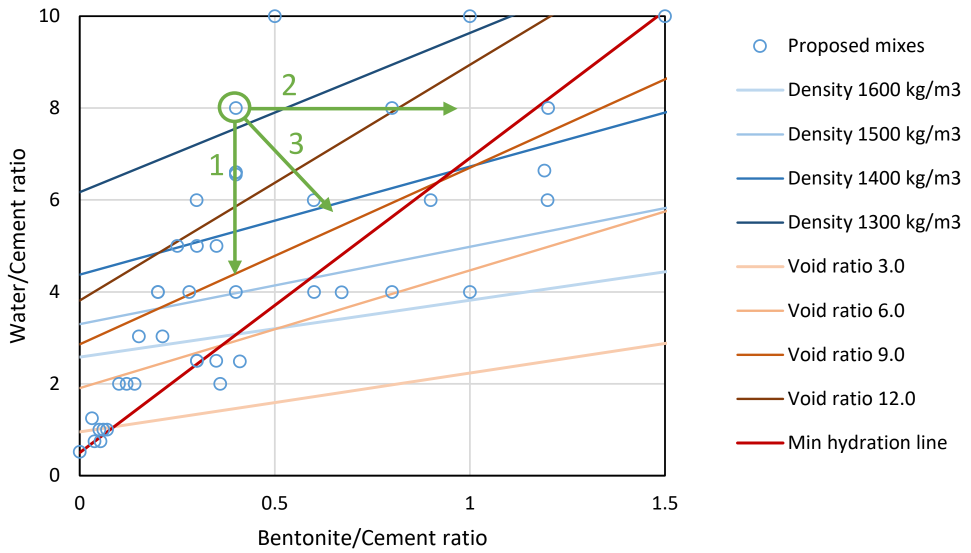

Figure 2: Bentonite/cement ratio against water/cement ratio (a sub-section of Figure 1b), showing potential adjustments to a grout mix starting at water/cement ratio of 8.0.

5. Conclusions and further work

This paper has considered relationships between the proportions of the constituents (cement/bentonite/water) and the resulting engineering properties of cement-bentonite grout using some limited data from the literature. An interaction diagram has been proposed to summarise the existing understanding and guide the design of and testing of grout mixes in the laboratory and during their use on site. A very wide range of cement-bentonite grout mixes have been proposed and tested, not all of which are likely to be suitable for geotechnical instrumentation in soils (some with low water/cement ratios have strengths typical of concrete). It has been found helpful to plot proposed mixes as water/cement ratio versus bentonite/cement ratio, along with lines of equal void ratio and density, and what is referred to here as the 'minimum hydration line' which approximately indicates the amount of water required to fully hydrate the cement and bentonite. An example is given on how this can guide adjustments to mix design. The compressive strength of the grout is dominated by the water/cement ratio, although adding bentonite does also increase the strength, while permeability is mainly dictated by the void ratio of the grout. Uncertainties over the constituent materials, preparation methods, and whether the grouts separated, means that some care has to be taken in using the results presented, and it is always recommended that grouts are mixed and tested in the laboratory prior to use on site.

Cement-bentonite grouts are a relatively unexplored and tested form of grout, and further work is needed to better understand how these materials behave. It should be noted that there is other experimental data beyond that used here, for example the PhD thesis by Durham (1996) contains further data on strength and viscosity that could be investigated. However, good quality laboratory work and results are required to:

- Better understand the 'minimum hydration line' and particularly the mixing and separation behaviour (as well as other performance) of grouts sitting above and below it;
- Give more values for the permeability of grouts, to complement those from Contreras *et al* (2008);
- Provide data on stiffness (Young's modulus) and the volume stability of grouts (for applications where the grout remains above the water table), for which there is currently very little information.

If this data is obtained, it would be possible to develop and extend Figure 1 in this paper, to further guide on how mix proportions and preparation influence the final engineering properties of cement-bentonite grouts.

Acknowledgements

Some of the cement-bentonite grout mixes presented in Table 1 were compiled from the literature by Dishon Mugo, who also experimented with various plotted relationships between grout constituents and strength/ permeability, as part of his University of Southampton MSc dissertation project (Mugo, 2020).

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