Plastic Concrete for Cut-Off Walls: a Review ⋆

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Abstract

The remediation of earthen dams is of growing interest worldwide. Plastic Concrete cut-off walls hereby provide an effective method to control dam seepage. However, Plastic Concrete material behaviour is not yet thoroughly understood. The review presented here confirms that Plastic Concrete may be considered to be a low-strength, low-stiffness impervious concrete with high deformation capacity under load, but also supports the need for further investigations into the mechanical and hydraulic material properties. This review provides an important opportunity to advance in the understanding of the material behaviour of Plastic Concrete and make a contribution towards a more realistic design of Plastic Concrete cut-off walls.

Keywords: Plastic Concrete, cut-off wall, design, review, dam remediation

1. Introduction

1.1. Background

The worldwide ageing infrastructure is a reason for concern in many countries. Unfortunately, only when a catastrophic failure of some infrastructure occurs, this topic obtains public awareness. A key example for the systematic, catastrophic failure of embankment dams and levees occurred in 2005 during the Katrina and Rita Hurricanes in the North-American Gulf Shore area [1].

Various failure modes are possible for earthen dams, ranging from dam overtopping and inadequate maintenance to foundation defects and slope instability. The latter generally occurs through water seepage below the dam body causing a reduction in internal friction and causing the dam to slip. Therefore, major concern has been raised regarding dam safety and various dam repair and remediation programs have been initiated worldwide. A common solution to counter

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dam seepage is the design and construction of cut-off walls. The planned cut-off wall is hereby extended into an underlying impervious stratum, e.g. rock [2], see Figure 1. The most effective cut-off walls for seepage control can be constructed with excavated slurry-trench walls, especially for greater depths [3].

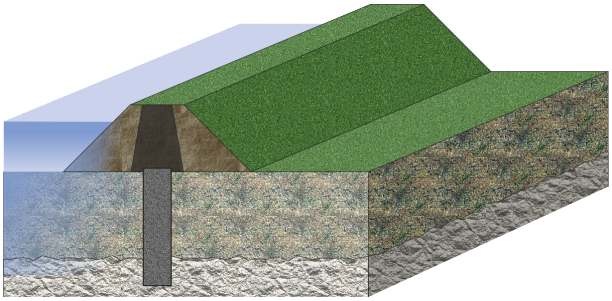

Figure 1: Schematic overview of a cut-off wall below an earthen dam

In a first step a slurry wall trench is excavated using clamshell excavators or hydromill trench cutters (see Figure 2, left). The trench is hereby filled with a support fluid in order to stop the excavated trench from collapsing. Most commonly bentonite or polymer support fluids are used. Before the backfill material can be placed, the support fluid used during excavation has to be replaced by a clean support fluid with defined material properties [4] (see Figure 2, centre). The backfill material is thereafter placed using the tremie method. The backfill material is hereby placed through the so-called tremie pipe, whereby the lower end of the tremie pipe always remains below the concrete surface (see Figure 2, right). As backfill materials a wide range of possibilities exist, however, a growing interest has arisen in Plastic Concrete due to the materials' suitable characteristics.

Plastic Concrete is hereby characterised through a high deformation capacity under load, which is of great advantage when ductile walls are needed when significant bending strains are expected due to unequal deformations of the cut-off wall, large annual reservoir fluctuations or significant seismic events [1, 2]. Especially the latter has lately been of strong research interest, since few backfill materials can withstand these high deformation [5, 6]. The high deformation capacity of Plastic Concrete in turn decreases both rupture probability and crack opening width, which would incur in material permeability increase [1, 6]. An example of cut-off wall deformation due to reservoir fluctuation and dam consolidation can be seen in Figure 3. Plastic Concrete has therefore been widely used worldwide in dam remediation for many years, with projects like the Sylvenstein Dam (Germany) [7], Hinze Dam (Australia) [8], Bagatalle Dam (Mauritius) [9] or Karkheh Dam (Iran) [10].

1.2. Problem

Despite its indisputably beneficial material properties, Plastic Concrete has not yet been thoroughly studied. To date, the design of cut-off walls considers Plastic Concrete to be a linear-elastic material. Its undoubtedly existing

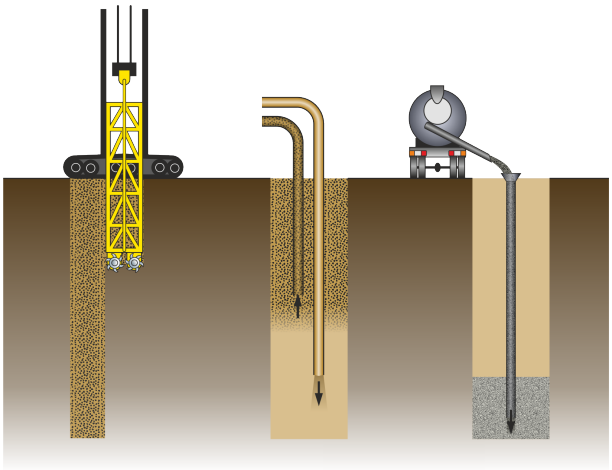

Figure 2: Overview of the construction of a slurry trench wall using a hydromill trench cutter (left) support fluid replacement (centre) and concrete placement using the tremie method (right)

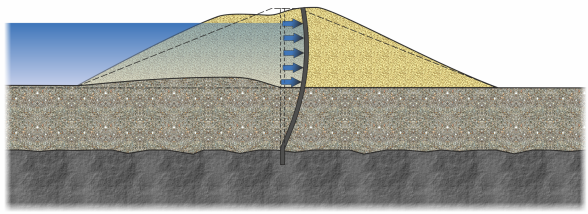

Figure 3: Schematic overview of cut-off wall deformation after dam consolidation and reservoir fluctuation, as well as original state (dashed lines)

ductile and plastic behaviour in the ultimate limit state as well as its clearly viscous behaviour during serviceability are neglected not least due to the lack of appropriate constitutive laws and substantiated scientific investigations. Few studies have been large enough to provide reliable estimates of material behaviour under load during a prolonged period of time and therefore have failed to systematically develop a constitutive law for Plastic Concrete.

1.3. Focus & Research Questions

This paper therefore aims to critically review the existing literature in Plastic Concrete and proposes general statements and reference values with which the design of Plastic Concrete can be enhanced to reflect material behaviour more realistically. Qualitative content analysis was used for this purpose.

This paper begins by describing the mix design of Plastic Concrete including the materials used as well as the variations in mixture composition and their influence on the fresh properties of Plastic Concrete. The third chapter discusses the significant findings regarding the mechanical behaviour of Plastic Concrete, most notably its material strength, elastic modulus, creep and relaxation properties. The hydraulic behaviour of Plastic Concrete is covered in chapter four. The final chapter draws together the key findings of this paper and aims to establish reference values which may be used for Plastic Concrete cut-off wall design.

2. Mix Design

2.1. Source Materials

Contemporary standard concrete is considered a five-phase construction material composed of cement, water, aggregate, additions (e.g. supplementary cementitious materials) and admixtures. Plastic Concrete can also be considered a five-phase construction material, however, in differing proportions to those usually mixed with standard concretes and containing bentonite as an additional constituent to obtain a highly ductile and impermeable material. However, the composition of Plastic Concrete is not limited to the aforementioned components and could be produced using other supplementary cementitious materials or other physically water-binding additions.

2.1.1. Cement

For Plastic Concrete two main choices exist. The International Commission on Large Dams (ICOLD) recommends within its Bulletin 51 [11] the use of blast-furnace (BLF) or pozzolan (POZ) cement since these types of cement have a stronger resistance against chemically aggressive water, as is also common knowledge within concrete technology [12, 13, 14]. In concrete construction it is also known, that through the use of BLF cement, concrete strength development at early age is much slower than with ordinary Portland cement [1, 12, 13, 15]. With this, when the secondary slurry-trench element is cut between two previously tremie-placed primary elements, while the tremie concrete is still of

low strength. In addition, the regional availability of BLF or POZ cements may also be a limiting factor in cement type selection.

2.1.2. Bentonite

Bentonite is a weathered rock composed of clay-like minerals which was first discovered in 1898 in Fort Benton, MT (U.S.A.) and is an alteration product of volcanic ash [16]. Although the bentonite discovered in Fort Benton is mainly composed of montmorillonite minerals ($\geq$ 80 wt-%), the term bentonite is however now well established and encompasses any clay-rock composed of smectite minerals, which in turn dominate the physical properties of the rock [16].

Smectite minerals form platelets composed of three layers. The most common smectite mineral, montmorillonite, consists of two SiO_4-tetrahedron on opposite sides of an AlO_6-octahedron [17, 18]. Due to the partial, isomorphic substitution of some cations a layer charge is generated, which is in turn counter-balanced by other cations within the interlayer space. Most commonly the interlayer cations are Ca^{2+}, Mg^{2+} or Na^{+} which neutralise the negative surface charge, and account for the two main bentonite groups Na-bentonite and Ca-bentonite (which commonly includes magnesium-bentonites) [19, 20, 18]. Furthermore, the weak layer charge permits the interlayer cations to adsorb and retain water molecules [19, 21]. The water adsorption capacity of sodium and calcium bentonite is however disparate, with Ca-bentonite adsorbing 200-300% water, while Na-bentonite can adsorb up to 600-700% of water [18, 22]. This water adsorption phenomena causes the clay minerals, especially montmorillonite to significantly increase in volume, multiplying its starting volume manifold. More recent research has also found that other physically water-binding additions (e.g. sepiolite, silty clay, etc.) can be used to effectively produce Plastic Concrete, although with some limitations [23, 24]. Bentonite has however remained of utmost importance in recent years, since bentonite's heavy metal absorption capacity has lead to growing interest in the application of bentonite for containment barriers for waste water or radioactive waste [25, 26, 23].

2.1.3. Aggregates and Admixtures

The most important criteria for the choice of aggregates in Plastic Concrete is the maximum grain size, due to the high segregation risk of fresh Plastic Concrete. This is caused by the relatively high w/c-ratio and the need to use bentonite as a stabilising agent (see subsection 2.2). Therefore, aggregates are generally limited to sands and fine to medium gravels. Most specifications have limited maximum grain size to $d_{max} \leq 22\ mm$ [2, 27] and practical applications predominantly limit maximum grain size to $d_{max} \leq 12\ mm$.

Furthermore, the fine particle content is also partially regulated to guarantee the necessary flowability [27]. It should however be noted that it is often difficult to meet specific grading demands at building sites in some countries. Furthermore, rounded aggregate is preferred as this type of aggregate further enhances the flowability of tremie concrete [28]. Moreover, the type of aggregate used is regulated by the exposure to any aggressive contaminant, with quartz based aggregate being the preferred aggregate type [28].

Various types of admixtures are also used in Plastic Concrete mix designs. Most often, retarding admixtures are used to slow down concrete setting and prevent premature concrete stiffening during tremie placement [2]. With this, a longer workability window is achieved and longer slurry trench elements can be produced, for which concrete placement with the tremie method can be safely finalised. Depending on Plastic Concrete mixture composition varying amounts of retarding admixtures may be added normally ranging from 1 wt-% to 2.5 wt-% of cement content, with special care being necessary when constructing long slurry-trench elements [8].

In some cases superplasticizing admixtures are also used to ensure better and more controlled workability of the Plastic Concrete mixture. It should however be noted that the effectiveness of modern polycarboxylate ether-based superplasticizers (PCEs) is negatively affected by the presence of clay minerals, especially montmorillonite [29].

In most instances, tap water is generally suitable for Plastic Concrete production. However, untreated water or water with high ion concentrations may affect bentonite dispersion or hydration process and should therefore be tested in trial mixtures if required [30].

2.2. Mixture Composition

As mentioned previously, Plastic Concrete is composed of cement, bentonite, aggregates, admixtures and water. In contrast to standard concrete, the w/c-ratio of Plastic Concrete is much higher, with values ranging from 3.3 to 10 [11]. The cement content is also significantly lower than that of standard concrete, rarely surpassing the 200 kg/m^3 mark and even being as low as 80 kg/m^3.

In Figure 4 five different concrete mixtures are shown, of which three correspond to Plastic Concrete mixtures. The concrete example from [12] represents a standard concrete with 20 MPa compressive strength at 28 days. The middle three mixtures are examples for Plastic Concrete with an approximate compressive strength of 1.30 MPa at 28 days [31, 32]. Finally, a mixture composition by [33] of a single-phase diaphragm wall material with 1 MPa compressive strength at 28 days is given for comparison.

As can be seen, the Plastic Concrete mix design is a combination of standard concrete and single-phase diaphragm wall material. The use of aggregates (most notably sand and fine gravel) in somewhat reduced quantities compares to the composition of standard concrete. The density of Plastic Concrete is also similar to that of concrete ranging from 1.9 g/cm^3 to 2.3 g/cm^3 and enough to effectively displace the bentonite slurry within the slurry trench element without mixing during tremie placement. The w/c-ratio on the other hand compares to that of single-phase diaphragm wall materials, exceeding by far 1.0, implying the existence of a far coarser micro-structure. Also, the use of bentonite as a stabilising admixture is comparable to that of single-phase diaphragm wall materials.

It should be emphasised however, that the in-situ composition of the backfill material is also dependent on the adjacent soil properties and especially on the casting method used. However, when Plastic Concrete is correctly placed

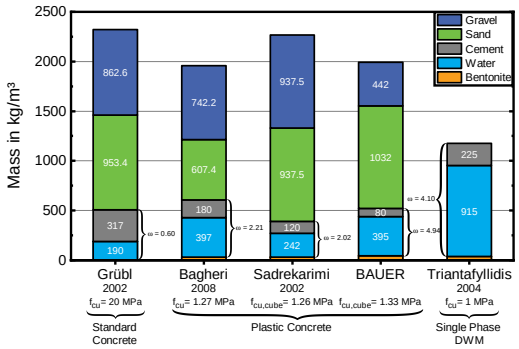

Figure 4: Representative examples of Plastic Concrete mix designs and their corresponding compressive strength

using the tremie method (see subsection 1.1) the best material properties can be obtained, which are closest to the target properties.

2.3. Mixing Sequence

Across the literature the Plastic Concrete mixing procedure is not consistent. Various options are presented, which are schematically shown in Figure 5.

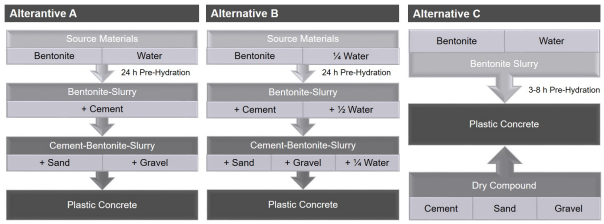

Figure 5: Representative examples of Plastic Concrete mixing sequences

Alternative A is the most commonly described variant in literature [31, 32, 34, 35, 36, 37, 38, 39]. In this, bentonite and water are gradually mixed together and then let to hydrate for up to 24 h. After this, cement is added to the bentonite-suspension and thereafter the aggregates are added. Alternative B [23] has a similar mixing sequence to alternative A, however the addition of water is hereby split into three separate stages. The bentonite slurry is also hydrated for up to 24 hours, before cement, sand, gravel and the remaining water are added in two separate stages. Finally, alternative C is an often used mixing sequence in practical application, whereby cement and aggregate are mixed to a dry compound, whilst bentonite and water are mixed into a slurry [7]. The bentonite slurry is then mixed with the dry compound to obtain the Plastic Concrete mixture, whereby the bentonite slurry is hydrated from 0 hours to 8 hours before use. It should be noted however, that due to the differing mixing

sequence and hydration time, varying results can be expected in terms of mechanical properties and permeability values. This is most likely the fact, as the bentonite hydration phase is different for the three aforementioned alternatives, which in turn affects the void filling in the hardened cement paste. In addition, the hydration of bentonite is however not only dependant on the aforementioned differences between bentonite types (see subsubsection 2.1.2) but also on the type of mixer and thus the induced shear rate $\dot{\gamma}$. For any given mixer it can be seen that the higher the maximum achievable shear rate $\dot{\gamma}$ is, the shorter the hydration time required for bentonite samples will be [40].

However, to date, only Fadaie et al. have studied the effect of dry and saturated bentonite on the mechanical properties of Plastic Concrete [41]. In their study, the authors found that the mechanical properties are nearly identical for samples were bentonite was added in a dry state and those where bentonite was hydrated for 24 hours. Furthermore the difference in mechanical properties is further decreased with increasing sample age [41]. Due to scarce scientific evidence in literature of the influence of the mixing sequence on Plastic Concrete properties, this topic should therefore be systematically studied in future research.

2.4. Fresh Properties

To ensure the correct placement of concrete, which in turn enhances hardened concrete quality, the fresh properties of Plastic Concrete mixtures have to be controlled, especially concrete flowability (often referred to as "slump") during the whole casting process. Therefore, the fresh properties must be controlled not only during inital placement, but also measure the thixotropic and flow retention characteristics of the concrete over time [42]. Despite the complexity and relevance of concrete rheology it is still not uncommon for simple concrete testing procedures (e.g. slump test, flow table test, etc.) to be used to determine the fresh properties of concrete [42]. It should be noted that many problems in diaphragm walls may be attributed to the use of inadequate concrete mixes resulting from poor concrete specifications due to deficient or simplistic testing procedures [42, 43].

For Plastic Concrete placed with the tremie method various guidelines and standards exist, which require specific values of concrete fresh properties. Concrete flowability is generally controlled through the water content and superplasticizing agent content, however the stability of the Plastic Concrete has to be closely monitored. For more detailed information regarding the various fresh concrete testing methods applicable for the tremie method (e.g. slump test, flow-table test, etc.) reference is made to the EFFC/DFI Guide to Tremie Concrete for Deep Foundations [43]. Scientific fundamentals on concrete rheology can be found in [44].

3. Mechanical Behaviour

3.1. Plastic Concrete Strength

The mechanical behaviour of concrete samples is most commonly related to the samples' compressive strength. However for cut-off wall design the knowledge of Plastic Concrete's tensile strength as well as multi-axial strength is also of utmost importance.

3.1.1. Unconfined Compressive Strength

General. The strength of Plastic Concrete can be characterised with various parameters, most commonly however the unconfined compressive strength (UCS) is herefore used. In concrete technology, the w/c-ratio is the most commonly used parameter affecting concrete strength, whereby a lower w/c-ratio incurs in higher concrete strength [12, 13]. Various studies have tested the UCS of Plastic Concrete with varying mix design and is summarised in Figure 6 [31, 32, 34, 35, 36, 37, 38, 45, 46]. The experimental data plotted in Figure 6 corresponds to cylindrical Plastic Concrete specimens with a height-to-diameter ratio of 2.0 (with varying size) produced with common mixture compositions and tested at 28 days of age. The data shape indicates which testing standard was used and is depicted in the graph legend.

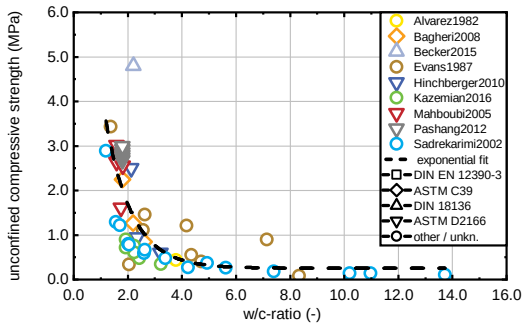

Figure 6: Overview of the UCS of Plastic Concrete at 28 days as a function of w/c-ratio

The graph shows that, as would be expected, there is a gradual decline in Plastic Concrete strength with increasing w/c-ratio, closely describing an exponential trend. In addition, some authors [32, 35] use a high w/c-ratio far exceeding commonly used w/c-ratios. However, due to the presence of bentonite the effective w/c-ratio is smaller, since the bentonite absorbs water into its structure reducing the readily available water for cement hydration. Although the water binding capacity of bentonite is different for Na-based and Ca-based bentonites, as described in subsection 2.1, the existing literature fails to analyse the contending behaviour of cement and bentonite for the available water and the likely interaction between these. In more recent studies, first steps have been made to predict the compressive strength of Plastic Concrete

using computational methods (e.g. artificial neural networks [47, 25]), however further research into this field is needed.

In concrete technology and design, standard concrete normally achieves a fracture strain of approximately 0.2% to 0.3% when tested under standardised unconfined compression conditions [12]. It is furthermore of common knowledge that the fracture strain increases with increasing concrete strength, however the post-cracking behaviour is far more brittle the higher the concrete strength is [12]. Plastic Concrete is therefore expected to have a higher fracture strain than ordinary concrete and a far more ductile post-peak behaviour. This behaviour has been corroborated by various studies, which identify an achievable strain at failure for Plastic Concrete between 0.5% and 1.0% in unconfined compression tests [46, 34, 48]. However, the aforementioned guide values are also dependant on loading speed, since concrete is a crack sensitive material [15].

Loading Rate. Since Plastic Concrete is commonly placed as a cut-off wall material below earthen dams, the material is subject to lateral forces induced through reservoir fluctuation, dam consolidation and seismic events. On the one hand reservoir fluctuation and dam consolidation happen at a very slow speed, whilst seismic events induce high loading rates on the cut-off wall. It is therefore important to comprehend the material behaviour in both cases.

With increasing loading speed, the measured concrete strength increases as the possibility of crack propagation around aggregate particles is reduced favouring particle rupture [15, 49]. At very high rates of loading additional inertial effects may further occur [15]. At very low loading speeds, creep deformation may also occur in addition to elastic deformation, causing concrete testing to determine lower compressive strength [15, 12, 49].

Therefore the standards referring to compressive strength testing of concrete all define a specific loading speed. In EN 12390-3 [50] the loading speed for concrete specimens is set to 0.6 ± 0.2 MPa/s, ensuring specimen failure to take place after 60 to 90 seconds. According to the German National Annex the loading speed may also be adjusted for specimens with a compressive strength above 80 MPa or below 20 MPa. ASTM C39/C39M [51] establishes that a rate of movement corresponding to a specimen stress rate of 0.25 ± 0.05 MPa/s should be applied. On the other hand, geotechnical testing standards for soil such as DIN 18136 [52] and ASTM D2166/D2166M [53] use strain rate as the defining loading speed, which should be 1% and 0.5% - 2% of the sample height per minute, respectively.

Kazemian et al. [45] found that the stress-strain behaviour of Plastic Concrete differs from that of ordinary concrete (not linear between 0% to 40%) and, as expected, the standard loading speed is generally too high to measure stress-strain. Hinchberger et al.'s study [36] with strain controlled experiments also showed that Plastic Concrete is sensitive to varying compression rates, whereby higher compression rates (0.01 mm/min $>$ 0.001 mm/min) result in higher compressive stress values [36].

Therefore, it is expedient to adjust the standard loading speed of concrete testing standards for Plastic Concrete specimens to achieve measurable and

precise data. With Plastic Concrete compressive strength at 28 days ranging between 1 - 3 MPa, samples should be tested with a lower loading speed between 0.02 MPa/s and 0.03 MPa/s. For example, in DIN 4093 [54], which regulates the design of strengthened soil using jet grouting, deep mixing or grouting techniques, the loading speed is reduced to 0.05 MPa/s for samples with an expected compressive strength $f_{cyl,m} \leq 4$ MPa. This loading speed would also be in line with Plastic Concrete requirements and achieve failure after approximately 20 s.

Strength Development. Although most reference testing is carried out at 28 days it is known that concrete strength continues to increase after 28 days. Concrete curing hereby mainly depends on the cement strength class, cement type and w/c-ratio used [12]. Blast furnace cement (e.g. CEM III) develops initial strength far slower than ordinary Portland cement (e.g. CEM I), however increases steadily far beyond the 28 day mark due to the latent hydraulic properties of blast furnace slag [13, 12]. Furthermore, the cement strength class also influences concrete strength development, with higher cement strength classes causing a more rapid strength development due to their higher fineness [13, 12]. For strength development of standard concrete, the *fib* Model Code 2010 [55] gives an approximation for the time function of the concrete strength development β_{cc} as a function of a cement-strength-class-dependant coefficient s and concrete age t, as shown in Equation 1.

$$\beta_{cc}(t) = \exp(s \cdot [1 - (28/t)^{0.5}]) \tag{1}$$

In line with these considerations, it can therefore expected that Plastic Concrete has a very low hydration rate due to the use of a low cement strength class, a high w/c-ratio and partially through the use of blastfurnace cement. Various studies have examined the long-term strength of Plastic Concrete mixtures, for which an overview is given in Figure 7 [46, 31, 34, 38, 39].

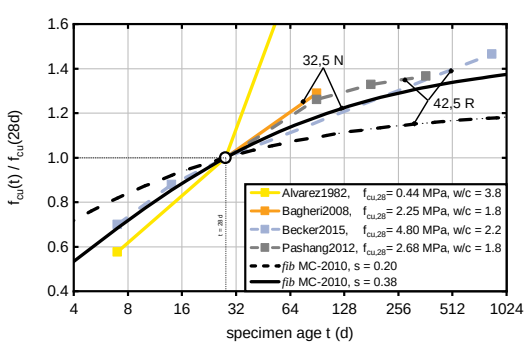

Figure 7: Overview of the UCS devleopment as a function of time

As can be seen, the strength development of Plastic Concrete is not finalised after 28 days, instead increasing steadily after 28 days. The studies also show

that due to the high w/c-ratio used the strength development of Plastic Concrete, at any given cement strength class, is slower than the *fib* Model Code 2010 estimates. It is also apparent that Plastic Concrete strength increases far beyond the 28 day mark and increases slowly before this date. However, from the literature review, it remains unclear how Plastic Concrete strength development affects the strain at failure of samples, since contradictory results can be found [39, 34, 48, 46, 37]. Against the background of concrete technology it should however be expected that strain at failure increases with increasing Plastic Concrete strength [12].

The knowledge of the long term strength development of Plastic Concrete is of utmost importance, since cut-off walls are constructed for design periods far exceeding 25 years. It is therefore not essential to test characteristic compressive strengths of Plastic Concrete samples at 28 days and can instead be tested at a higher age. Caution is hereby advised, since a very low strength development may also compromise the construction operation efficiency due to the alternating sequence of primary and secondary panel construction and should therefore be considered during the design phase.

3.1.2. Tensile Strength

Next to the unconfined compressive strength the uniaxial tensile strength (f_{ct}) is an important parameter for the design of concrete structures. For standard concrete the uniaxial tensile strength averages 10% of unconfined compressive strength f_{cu} [13]. This f_{ct}/f_{cu}-ratio is however not constant and e.g. decreases with increasing time and compressive strength f_{cu} [13]. Furthermore, the ratio is affected by the type of aggregate, aggregate grading, as well as curing conditions.

The *fib* Model Code 2010 suggests that the mean tensile strength f_{ctm} can be estimated from the characteristic compressive strength f_{ck} following Equation 2 for concrete grades $\leq$ C50 [55].

$$f_{ctm} = 0.3 \cdot (f_{ck})^{2/3} \tag{2}$$

For a Plastic Concrete sample with a characteristic compressive strength f_{ck} of 2.0 MPa this would incur in a mean tensile strength f_{ctm} of 0.48 MPa, suggesting a f_{ct}/f_{cu}-ratio of 0.24.

It should be however noted that the mean tensile strength f_{ctm} refers to uniaxial conditions, whilst tensile strength testing of concrete specimens most commonly occurs with the splitting tensile strength $f_{ct,sp}$ test, whereby the conversion between both values has not been finally resolved in literature. For Plastic Concrete solely the USACE REMR-GT-15 report also tests the splitting tensile strength of concrete, with splitting tensile strength $f_{ctm,sp}$ averaging 13 % of the ultimate compressive strength f_u of the samples tested [56].

The exact tensile strength to compressive strength relationship f_{ct}/f_{cu} for Plastic Concrete remains however unclear and should therefore be an important part of further investigation. It may seem expedient, against the background of

concrete technology, to estimate Plastic Concrete tensile strength to be 10 % to 20 % of compressive strength.

3.1.3. Multi-Axial Load-Bearing Capacity

In cut-off walls Plastic Concrete is intrinsically submitted to a multi-axial stress state. It is therefore of utmost importance to also understand the multi-axial behaviour of Plastic Concrete.

Firstly, it is expedient to remember that standard concrete failure under a uni-axial compressive force occurs through the inherent development of a transversal tensile stress and the exceedance of the concrete tensile strength [15]. The concrete specimen hereby fails through the development of cracks parallel to the direction of main loading exhibiting a brittle behaviour [13]. This lateral strain may however be hindered through the application of a compressive force perpendicular to the direction of main loading, hereby increasing the overall compressive load-bearing capacity of a concrete specimen [15]. Similarly therefore if a triaxial compression is applied with high lateral stresses, the concrete load-bearing capacity increases manifold [13]. This increase is also known to be more pronounced the lower the ultimate compressive strength of concrete is [12]. The failure however no longer occurs through the exceedance of tensile strength but instead through crushing, incurring in a change in failure towards a more ductile behaviour [13]. An overview of the failure mode change depending on the stress applied can be found in [57].

For Plastic Concrete a similar behaviour to standard concrete can be expected. Since the uniaxial compressive strength is low, the multi-axial load-bearing capacity increase can be expected to be more pronounced. However, this increase is likely limited due to the high water and moisture content of Plastic Concrete samples. Various studies have also confirmed the change in failure mode with increasing confining pressure for Plastic Concrete samples [39, 34, 36, 37, 38]. The specimens tested at higher confining pressures not only exhibit a higher compressive load-bearing capacity and elastic modulus [39], but also a more ductile behaviour and an overall higher strain at failure [34, 37, 38, 39]. An example of this change in behaviour with increasing confining pressure can be seen in Figure 8 [38].

3.2. Elastic Modulus

The elastic modulus E of concrete is primarily determined by the elastic moduli of its components cement paste and aggregate, as well as the volumetric proportions of the materials in the mix, and may be estimated through composite theory [15]. Therefore, generally speaking, an increase in water content or a decrease in cement content causes the elastic modulus of concrete to decrease [15]. Furthermore, with increasing degree of hydration the elastic modulus increases, whereby the elastic modulus increase precedes the compressive strength increase [12]. In Figure 9 the elastic modulus of Plastic Concrete is plotted over the corresponding compressive strength [46, 34, 36, 45, 37, 32, 58].

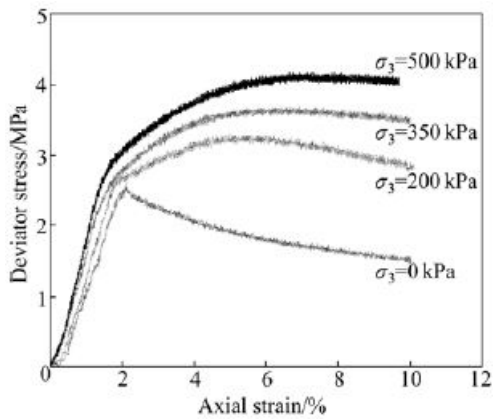

Figure 8: Variation of deviator stress versus axial strain for unconfined and triaxial compression tests [38]

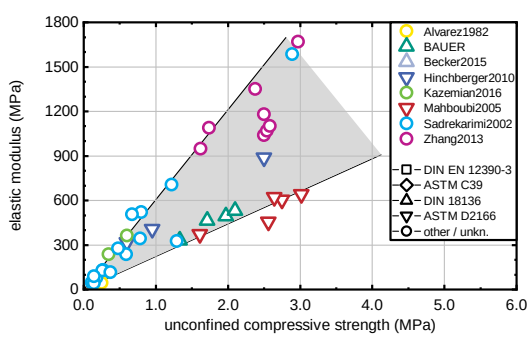

Figure 9: Elastic modulus as a function of the compressive strength at 28 days

Similarly to ordinary concrete, the elastic modulus of Plastic Concrete increases with increasing compressive strength. However, it hereby becomes apparent that the testing procedure used clearly influences the obtained elastic modulus, in-line with varying definitions of elastic modulus underlying the individual testing procedures. The "elastic modulus" determined with concrete testing standards (Zhang et al. [58]) is higher than that obtained from geotechnical testing standards (e.g. Mahboubi et al. [37]). This is most likely due to the deformation measurement techniques used, since concrete standards measure specimen deformation in-situ (e.g. strain gauges) while geotechnical standards generally use the machine displacement to obtain specimen deformation. Based on the literature review, and as shown in Figure 9, the elastic modulus of Plastic Concrete can be assumed to be in the range of 300 to 1500 MPa dependant on the testing standard used.

Since the elastic modulus of concrete directly relates to it's compressive strength, it is important to note that the requirement of a characteristic compressive strength f_{ck} (defined statistically as the 5-percentile value) is not expedient since this automatically relates to an increase in the elastic modulus [7]. It is therefore purposive to define a mean compressive strength f_{cm} which is required for the proposed cut-off wall and hereby also establish the targeted elastic modulus. This further substantiates the fact, that the testing conditions should therefore be specified during planning and tendering of projects.

In addition, the target elastic modulus of Plastic Concrete should be similar to that of the surrounding soil and should not exceed five times the latter [11]. This has also been confirmed by some numerical studies into the deformation of cut-off walls due to high overburden or seismic load, which show that a higher elastic modulus of the backfill material causes higher strain and stress within the cut-off wall, which in turn may incur in cut-off wall seepage or even failure [6, 59].

3.3. Creep and Relaxation

When concrete is subjected to a load, concrete firstly reacts elastically. However, besides elastic strain components, concrete also presents a non-linear stress-strain behaviour when subjected to sustained loading. Strain hereby increases gradually with time due to concrete creep. The creep coefficient φ is hereby the most common engineering approach to estimate concrete creep and is defined according to *fib* Model Code 2010 as the quotient of the concrete creep strain ε_{cc} and the concrete elastic strain ε_{ci} following Equation 3 [55, 15].

$$\varphi(t, t_0) = \frac{\varepsilon_{cc}(t, t_0)}{\varepsilon_{ci}(t_0)} \tag{3}$$

Various parameters affect the creep behaviour of concrete. With an increasing cement content and increasing water content, concrete creep increases as it is the cement paste phase which undergoes creep [13]. Concrete creep is also dependant on the age at loading, with creep increasing disproportionally the

younger the concrete is at loading [60]. Therefore, depending on the conditions present the final creep coefficient φ_∞ may vary greatly, normally ranging between $1 < \varphi_\infty < 3$ for standard concrete [15].

On the contrary, if a stressed concrete specimen is subjected to a constant strain, the specimen stress will gradually decrease with time, known as relaxation. Both creep and relaxation are based on the same molecular mechanisms and therefore all influences affecting concrete creep also affect concrete relaxation [12].

Taking into account the aforementioned influencing parameters, it should be expected that Plastic Concrete has a greater creep and relaxation behaviour than standard concrete, with various studies having confirmed these expectations [36, 61, 48]. Firstly, the very high w/c-ratio likely incurs in high water loss and specimen deformation. In addition, due to the very slow strength development of Plastic Concrete mixtures the specimen loading will likely occur at a low degree of hydration furthering concrete creep. Beckhaus et al. suggest a final creep coefficient $\varphi_\infty \geq 2$ for Plastic Concrete samples, which was derived from results on soil samples solidified with the jet grouting technique [61]. It can be expected however that Plastic Concrete mixtures may have even higher creep coefficients (e.g. $\varphi_\infty > 3$).

Hinchberger et al. [36] studied the effect of constant axial strain on the stress behaviour of Plastic Concrete and found that Plastic Concrete shows significant stress relaxation effects with the measured stress reducing approximately 30% after an 8 h period, with the reduction having not yet stabilised up until this point. All in all, Plastic Concrete is expected to have a stronger relaxation behaviour than standard concrete and therefore a time-dependant constitutive model is required for Plastic Concrete [36].

4. Hydraulic Behaviour

Since seepage control of earth dams is the main purpose of a cut-off wall, the hydraulic conductivity of Plastic Concrete is one of the most important parameters to be tested. Despite this, no specific testing standard exists for the measurement of Plastic Concrete permeability. Therefore, standard test methods from geotechnical engineering as well as concrete technology are used.

The hydraulic conductivity testing of concrete specimens can be foremost divided into two main testing groups, namely those under loaded and unloaded conditions, whereby in concrete technology material hydraulic permeability is normally tested without simultaneous loading, as reviewed by Hoseini et al. [62]. Despite most data reviewed corresponding to testing methods where permeability was measured after loading, in various practical applications (including Plastic Concrete) concrete is submitted to compressive or flexural forces while simultaneously being permeated through. Few testing methods exist for this purpouse, however geotechnical triaxial cells may be used for this purpose, with which the hydraulic conductivity k can be determined [63].

In addition, due to its low strength, degree of water-tightness and composition, Plastic Concrete is commonly tested following geotechnical testing

standards and not structural concrete penetration tests. An overview of some test results of hydraulic conductivity k without confining pressure is given in Figure 10 [31, 35, 34, 64, 65].

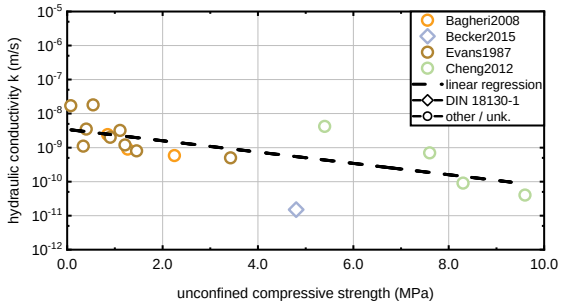

Figure 10: Hydraulic conductivity of Plastic Concrete over unconfined compressive strength

It can be seen that, similarly to standard concrete, the hydraulic conductivity of Plastic Concrete specimens decreases with increasing compressive strength. This may be ascribed to a reduced particle-cross linking and an increased air void content with increasing w/c-ratio i.e. decreasing compressive strength.

Moreover, it should be noted that current design procedure for Plastic Concrete does not account for the highly ductile behaviour of this material, whereby a high relaxation and creep potential have been shown to exist (see subsection 3.3). This behaviour is beneficial for Plastic Concrete hydraulic permeability, since it can prevent material stress peaks during loading and avoid the formation of cracks, which would incur in an increase in permeability. Some initial studies have shown that with deformation of approximately 70% of strain at failure, no significant increase in hydraulic conductivity occurs [48]. By contrast, crack onset in concrete generally occurs at approximately 20% of strain [48].

Only few studies also refer to the time-development of Plastic Concrete hydraulic conductivity, whereby a decrease in hydraulic conductivity over time is reported [34, 66]. This is in line with the strength development behaviour of Plastic Concrete (see subsubsection 3.1.1) and is likely caused by the progress of hydration and the consolidation of concrete microstructure [67]. In addition, crack self-healing and crack obstruction with the transported particles, amongst others, are also known to cause the permeability of concrete to further decrease over time [68]. Nonetheless, this aspect has not yet been finally clarified in literature.

Due to the time-development of Plastic Concrete permeability, some specifications allow for permeability tests at higher ages (e.g. 90 days), to achieve the required design permeability values [30, 27]. It may however also be contractually expedient to set 28-day control values, not as the design permeability but as a demonstration of design value achievement, to shorten the acceptance period of the construction services provided [30].

5. Conclusions

5.1. Summary

With the present article first steps are set out for a comprehensive understanding of Plastic Concrete material behaviour. With the acquired knowledge Plastic Concrete can be used to safely guarantee seepage control inside and below dams with a controlled material behaviour. All in all, the following considerations may be taken into account for Plastic Concrete cut-off wall design. More detailed information can be found in [69].

Mix Design. Plastic Concrete can be considered to be a low strength concrete with a low elastic modulus capable of sustaining larger strains than normal concrete. These properties can be achieved through the targeted selection of raw materials and mix design. The key component differentiating Plastic Concrete from ordinary concrete is the far higher w/c-ratio, for which the fresh concrete stability has to be controlled by low amounts of physically water-binding additions. Most commonly bentonite, a clay-rock composed of montmorillonite minerals, is added, however other additions may also be used. Finally, Plastic Concrete uses regular aggregate with a maximum grain size of 12 mm (due to the segregation risk) as well as including retarding admixtures to delay concrete setting in tremie placement.

Plastic Concrete mix design is similar to that of standard concrete with aggregate content ranging between 1300 and 1900 kg/m^3 and cement content lying in the range of 80 to 200 kg/m^3. The w/c-ratio generally ranges between 2.0 and 5.0, depending on target strength and source materials used. The mixing sequence has also been shown to influence material properties, whereby currently no standardised mixing sequence exists.

Mechanical Behaviour. The mechanical behaviour of Plastic Concrete is in line with that which can be expected from concrete technology. It should however be noted that much testing is conducted using geotechnical testing standards and not concrete testing standards, which is especially important when testing Plastic Concrete deformability i.e. elastic modulus.

Generally speaking, it can be ascertained that the compressive strength of Plastic Concrete increases with decreasing w/c-ratio. However, the w/c-ratio does not account for the addition of bentonite and therefore not consider the reduction in free water available for cement hydration. Plastic Concrete compressive strength normally lies between 0.5 to 2.5 MPa at 28 days, with compressive strength development being very pronounced, far beyond the 28 day mark. It may therefore also be expedient to test Plastic Concrete compressive strength at higher ages, e.g. 90 days. Furthermore, the loading rate should be adjusted to account for the low strength of the material and should be tested with a loading speed between 0.02 MPa/s and 0.03 MPa/s.

The strain at failure of Plastic Concrete is also far greater than that of standard concrete, where under compression a maximum strain of 1% can be achieved. The tensile to compressive strength ratio of Plastic Concrete is also

expected to be greater than that of standard concrete, lying in the range of 10% to 20%. Under multi-axial load, the load bearing capacity clearly increases with axial strains as high as 10%.

The magnitude of the elastic modulus of Plastic Concrete clearly depends on the testing standard used, due to differing definitions of elastic modulus and diverging specimen deformation measurement set-ups. The deformation modulus (geotechnical standard) of Plastic Concrete can therefore be estimated to 100-600 MPa, whilst Young's modulus (concrete standard) should be estimated in the range of 300-1800 MPa.

Due to the high w/c-ratio of Plastic Concrete, the creep and relaxation properties are more pronounced than those of standard concrete. With this, the final creep coefficient can be expected to be $\varphi_\infty \geq 3.0$. Therefore, the relaxation potential of Plastic Concrete is also notably higher than that of standard concrete. The higher relaxation potential of Plastic Concrete is in turn beneficial to prevent material stress peaks during loading and avoid the formation of cracks, which would incur in an increase in permeability.

Hydraulic Behaviour. The hydraulic behaviour of Plastic Concrete, and concrete in general, remains a relatively unstudied field, especially for testing under realistic stress conditions. For Plastic Concrete it has been shown that permeability decreases with decreasing w/c-ratio which is linked to a less porous material structure. The change in Plastic Concrete permeability over time is scarcely reported in literature, however a decrease in permeability over time has been shown to exist. It is therefore expedient that Plastic Concrete permeability testing is conducted at ages greater than 28 days (e.g. 90 days) to account for the permeability increase with time. Plastic Concrete permeability can therefore be estimated in the range of 10^{-8} to 10^{-9} m/s depending on testing age.

5.2. Unresolved Questions

Despite these promising results, questions remain which should be the purpose of further studies. Firstly, further research is required to examine the effects of the mixing procedure on Plastic Concrete hardened behaviour. The focus of these studies should be placed at understanding the interaction of water, bentonite and cement and to what extent the varying mixing procedures may alter the availability of water during cement hydration. Most notably reliable analytical methods must be studied to comprehensively characterise bentonite raw materials as this may shed light on the mechanism underlying Plastic Concrete behaviour and establish bentonite requirements. The understanding of these mechanisms is also of utmost importance to establish their influence on compressive and tensile strength of Plastic Concrete as well as creep behaviour. Furthermore, the creep and relaxation potential of Plastic Concrete should be intensively studied, since these have a significant impact on the material stress and in turn strongly affects cut-off wall design and dimensioning. On the other hand, the permeability changes in Plastic Concrete should be the subject of

further studies. A greater focus on the determination of Plastic Concrete permeability under simultaneous loading could produce important findings that account for a more realistic design of Plastic Concrete cut-off walls. For this, the development of a new testing method may also be necessary.

All in all, it may be summarised that the findings of this study have a number of important implications for future best practice. However, continued efforts are needed to further understand Plastic Concrete behaviour and ensure its correct application in cut-off wall design.

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