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Geotechnical Characterisation of a Sandy Loam Amended with Water Treatment Residual

Heather KERR[1], David G TOLL[2], Karen L JOHNSON[2]

[1]Isle Utilities, London, United Kingdom
[2]Durham University, Durham, United Kingdom
Corresponding author: Heather Kerr (heather.kerr@isleutilities.com)

Abstract

Water treatment sludges or residuals are a by-product of treating potable water. The land application of iron based water treatment residual (WTR) is common practise across the UK as a disposal method for this non-hazardous waste. However, WTR also has potential use in barriers and slope protection methods to improve resilience of infrastructure. Research by Kerr et al (2022 and 2016) and Kerr (2019) has shown that adding WTRs to soils can be beneficial to the soil's water holding capacity, hydraulic conductivity and shear strength at high rates of amendment. No investigations to date have examined the effect of WTR amendment on these important properties over numerous climatic cycles. This paper presents the geotechnical data obtained from testing weathered amended soils to understand the long-term effect of WTR amendment on a sandy loam. Additionally we examine the effect of WTR's water content during soil preparation and amendment, on the geotechnical characteristics of amended soils. We characterise and compare the properties of amended soils containing 2-10% WTR (by dry mass) and a 10% co-amendment using WTR and compost. The programme of tests included proctor compaction testing, unconsolidated undrained and consolidated undrained triaxial tests. Results show that soils amended with WTR exhibit higher shear strength compared to the control soil after climatic cycling, however co-amendment with WTR and compost showed the highest shear strength of all amended weathered soils.

Keywords: Water treatment residual, soil characterisation, soil remediation.

1. Introduction

Recently, the increasing cost to landfill waste and the requirement to move towards a greener economy has meant that water companies are required to find alternative disposal routes for the large quantities of water treatment sludges or residuals (henceforth referred to as WTR), a waste produced during the treatment of clean drinking water. WTR is a non-hazardous waste, primarily composed of soil constituents (SiO_2, inorganic minerals), the coagulants used to remove contaminants (that can either be aluminium-based, typically Al_2O_3 or iron-based, $Fe_2O3/FeCl_3/Fe_2(SO4)^3$), and organic components of the raw source water (Ahmad et al., 2016). The geotechnical properties of WTR across the world and the wide range of potential reuse options have been reported by e.g. Ahmad et al., (2016); Babatunde and Zhao, (2007), Ippolito et al., (2011), Turner et al., (2019). Disposal options for this waste have historically been to return to source, indefinite storage in sludge lagoons, dewatering and landfilling, sending to sewerage, or incineration. The option for companies to follow these methods is progressively infeasible through increasingly stringent environmental legislation, and there is growing awareness of this waste as a potential resource due to its mechanical and chemical properties.

A simple alternative that is already employed by a number of water companies in the UK, and across the world, is agricultural land application (Turner et al., 2019, Kerr et al., 2022). The quantity of WTR that can be spread to land is limited by the chemical and biological effects of such disposal, where application thresholds are predominantly associated with Al toxicity in Al-WTRs, nutrient availability, concentration of potentially toxic elements (PTE) and phosphorous immobilisation that may potentially limit plant growth. Environmental permits to spread WTR to land in the UK must demonstrate that its application does not adversely affect the soil quality, however there is ample evidence to show that WTR addition can provide benefits to agricultural soils when used as a substitute or amendment in small proportions (Babatunde & Zhao, 2007; Elliott and Dempsey, 1991: Titshall and Hughes, 2005; Kerr *et al.,* 2022). WTR application to soil is known to adjust the pH (increasing pH), improve soil structure (although only thus far in Al-WTRs e.g. Dayton and Basta, (2001)), water retention (Bugbee & Frink, 1985; Kerr *et al.,* 2022) and shear strength (Kerr et al., 2022), but there is exceptionally sparse data in relation to Fe-WTRs owing to the prevalence of Al as a coagulant. Here we show that the application of Fe-WTR to soil has vast potential geotechnical benefits, thus supporting multiple initiatives (environmental sustainability, net zero, UN Sustainable Development Goals 9, 12 and 15) to incorporate waste materials into soils in order to maintain, preserve or remediate this precious resource. WTR can be used to improve shear strength and hydraulic conductivity when used as a single amendment, as shown by Kerr et al. (2022).

A potential use of WTR is to enhance water retention properties in “climate adaptation composite barrier systems” capable of limiting the impact of a changing environment on buried geo-infrastructure, such as retaining walls and foundations. This is being investigated in the CACTUS (Climate Adaptation Control Technologies for Urban Spaces) project (Toll et al., 2022) being undertaken by a consortium of UK Universities: Durham, Cardiff, Dundee, Queens Belfast, Imperial College London and Newcastle. The project is undertaking systematic experimental and numerical modelling studies to understand the response of composite barrier systems, when subjected to extreme weather events and long-term climatic processes. The barriers comprise an upper water holding layer (engineered by addition of WTR to hold water during storms and wet periods), a vegetation layer that can remove water during drying periods (by evapo-transpiration) and a capillary barrier system to prevent water from entering or leaving the deeper soil layers in order to maintain a constant water content at the level where the geo-infrastructure is constructed. The barriers have the potential for use in slope protection, restricting water infiltration that can prevent rainfall-induced landslides, so the shear strength of the amended soil is an important property to investigate.

2. WTR material characteristics and characterisation

Water treatment residual (WTR) is produced when coagulants and flocculants are used to remove particulates and contaminants from source water, and thus the properties of WTR vary depending on a variety of factors including source water, type and dosage of coagulants (typically Al or Fe salts), extent of dewatering and chemical composition. Generally, WTRs consist of fine sands, silt, clays, precipitated metal coagulants, conditioning agents and colloidal organic matter, with the proportion of these being regionally dependent (O’Kelly, 2008). The polyelectrolytes used for water clarification are long-chained organic molecules that bind unwanted suspended particles in source water, and thus provide inherent shear strength in WTR flocs (Turchiuli and Fargues, 2004). Turner et al (2019) among others provide a detailed summary of WTR production, treatment and composition ranges from across the world, including chemical attributes. It is understood that the properties of WTR are widely variable around the globe.

The WTR used in this research was a ferric WTR containing anionic polyacrylamide with sodium acrylate and non-ionic potato starch, with river as the source water. The dry solids were 20±2%, pH of 4.7±0.5 and electric conductivity of 239±168 (mean of one year values) (Finaly 2015). The Fe% was 28.8±1.7, Al % 0.4±0.3, loss on ignition LOI550 % 48±2.7, total Carbon % 21.4±2.2. The particle density of air-dried WTR was 2.11 g/cm^3 (as determined by Kerr, 2018), which is higher than typical ranges of 1.83-1.99 g/cm^3 (O’Kelly, 2010). More generally, the WTR was 60% FeOOH and 40% organic matter and was obtained in a dewatered format (20% solids) from Mosswood Water Treatment Works (Northumbria Water Ltd.)**.**

The initial preparation of specimens was an important issue, as the structure of WTR can be different dependent whether it is wetted or dried to achieve the required water content. Owing to the high water content of the WTR (20% solids), some tests were undertaken on specimens prepared from both the wet and dry side. Specimens were tested in three states [1] immediately after preparation [2] at a given water content [3] after a number of drying and wetting cycles before preparation in order to provide an indication of how these materials would be affected in the long term. In each set of geotechnical testing, five soil types were tested: a control sandy loam soil, 10% WTR + 90% soil, 5% WTR + 95% soil, 2% WTR + 98% soil and a 10% co-amendment (5% WTR + 5% compost + 90% soil). The proportions of each soil type were calculated by dry mass of materials.

3. Geotechnical Properties

3.1 Water content

Because of permanent changes to WTR if oven drying, air drying of dewatered WTR was used to determine floc water content of WTRs. During air drying, one of three treatments were applied to samples, either undisturbed, lightly disturbed or broken down to the finest constituents. The temperature (20°C) and humidity (50%) were kept constant and the WTR was dried until a negligible change in mass was observed. The water content of each WTR was calculated following BS 1377:2 (1990).

Results show that the water content of air-dried WTR was found to be directly related to the level of disturbance of the material during drying. Undisturbed WTR dried much more slowly than the other materials and retained shape despite significant shrinkage and cracking. Lightly disturbed WTR retained large aggregates. Highly disturbed WTR became increasingly powder-like. WTR that has not been disturbed reached an air-dried water content of 36.3%, whereas highly disturbed WTR reached 29.1%.

Disturbance level	Initial water content	Air Dried water content	Reduction in water (free water)	Remaining floc water
High	1.464±0.08	0.291	81.4%	18.6%
Low		0.318	77.7%	22.3%
None		0.363	73.8%	26.3%

Table 1: Water content of WTR as air dried with different levels of disturbance.

It is important to note that the water content of WTRs is the greatest single cause of variation in the geotechnical properties (Xia, 1994, O'Kelly, 2010). During the drying process as water is removed from the WTR, the waste material develops unique floc structures owing to colloidal properties and high ion concentrations. Water contained within WTRs can be classified in three categories: free water, floc water and chemically bound water (O'Kelly, 2010 Xia, 1994). Free water is easily removed through dewatering, pressing or air drying the material. Floc water cannot be removed by air drying unless there is significant disturbance to the flocs during the drying process such as crushing, alternatively this water can be removed through the application of high temperatures. Bound water cannot be removed by oven drying and is considered part of the solid mass. Based on this rudimentary test, it appears that of the total water residing in the raw WTR, 73.8% is free water, thus 26.3% is floc water or trapped free water. This water is unable to be removed with air drying alone. Although current land spreading of WTR is based on the properties of dewatered sludge, the long-term effects of WTR application will reflect the geotechnical properties of the dried material, thus capturing this change is important. It is unknown whether the water present after air drying is chemically bound or plant accessible.

3.2 Proctor compaction tests

Proctor compaction tests (BS Light Compaction, BS1377:1990) were carried out on samples prepared in different ways, one from the wet side and two from air-dried. Material tested from the wet-side was prepared as follows;

- Dewatered WTR was added to the control soil at the appropriate proportion. The wet amended soil mixture was dried to a specified water content before a 2kg sample was taken for testing. The resulting compaction curve demonstrates the compaction characteristics of amended soil after initial blending, without any weathering, which is important for understanding the use of this material in earthworks.

All amended soils tested from the dry side used WTR that had been air dried for 3 months at room temperature, and had a water content of 25%.

- [A] Air-dried WTR was added to air-dried soil (~4% water content), and distilled water was added to increase the water content.
- [B] "Weathered" air-dried amended soil was tested. The amended soil had undergone several wetting and drying cycles before being used for testing. This was to understand the compaction characteristics of amended soils on a long term basis.

Comparing the compaction testing of conventional dry to wet and wet to dry amended soils had interesting results. The black curves represent [A] air dried and orange curves represent [B] "weathered" soil. Figure 1 shows that the control soil had a typical soil compaction curve that has a simple bell shaped curve, where the peak density is reached at optimum water content. Amended soils showed a far flatter, wider curve, with higher optimum water content and lower maximum dry density. Interestingly, compared to freshly dried amended soil, "weathered" amended soils (10% WTR and 10% co-amendment (5% WTR and 5% compost)) develop a curve characteristic more like the control soil, suggesting that the WTR has broken down into its finest fraction and does not retain floc moisture that would impact the compaction characteristics.

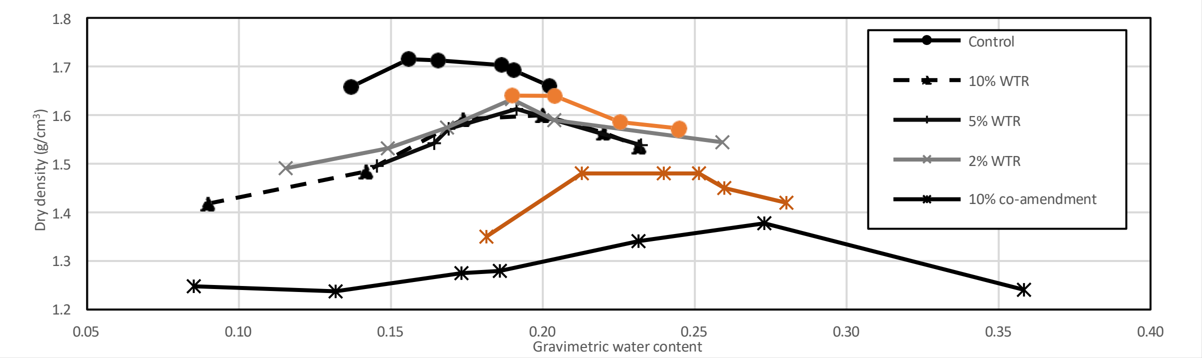


Figure 1: Compaction characteristics of amended soils compared to a control soil, completed dry to wet as per method A and method B (for "weathered" soil) shown as orange curves.

Figure 2 compares the compaction curves of amended soils tested wet to dry. Compared to Figure 1, the curves are very flat, and generally each amendment has a lower maximum dry density and optimum water content than the materials tested dry to wet. Although evident for 2% and 5% amendments, the 10% WTR material does not display the usual curve with changing water content, and instead progressively achieves a higher density as water content reduces. The reason for this trend was described by Wang et al (1993), who found that the dry density of WTR increases as water content decreases, with a maximum density achieved at zero water content. Similarly Hsieh & Raghu (1997) found that the material characteristics are different at the same water content when approached from wet side or the dry side, which can be attributed to the changing floc structure of WTR as water is lost. Ions that were in a soluble state within the floc water in wet WTR (e.g. Fe3+) are adsorbed into solid particles during drying, and new inter-particle bonding cements the solids together (Scott, 1980).

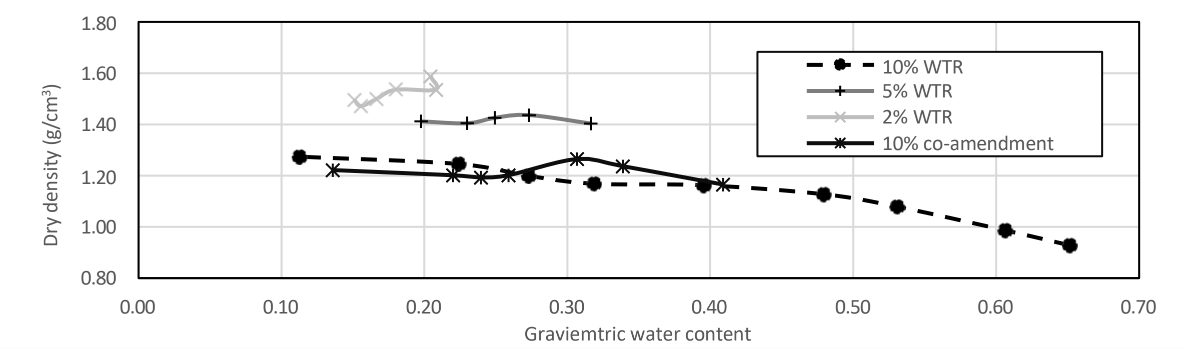


Figure 2: Compaction characteristics of amended soils completed wet to dry.

3.3 Unconsolidated Undrained Triaxial testing

Unconsolidated Undrained (UU) triaxial testing (BS 1377-7:1990) were carried out at a confining pressure of 100 kPa. Specimens were prepared in different ways to determine the shear strength characteristics of soils under different conditions. Initially, each of the five soil types were prepared to a dry density of 1.4 g/cm^3 using a static press. Specimens were treated in one of four ways after preparation,

1. Compacted and sealed
2. Air-dried to a set water content,
3. Air-dried and rewetted to a set water content (one cycle)
4. Air-dried and rewet over four cycles, and tested at field capacity

The first preparation method [Test 1] was followed to test for thixotropic hardening of samples. Soil specimens were tested every two weeks (n=3) for a period of three months to monitor change in strength over time. Tests 2, 3 and 4 investigate the shear strength of specimens at varying water contents through the initial drying and wetting cycle, and the long-term strength of the soils after four climatic cycles, which is sufficient for soils to reach equilibrium after remoulding (O'Kelly, 2013).

Tests on the compacted soil [Test 1] yielded no significant difference in the shear strength of specimens when comparing the material immediately after compaction and in subsequent weeks, which suggest there has been no thixotropic hardening of any of the four soil types over time. Figure 3 shows the reduction in shear strength over progressive climatic sequences. In general, higher proportions of WTR yields greater shear strength compared to lower amendment proportions. When testing after air drying to a water content of 0.31 [Test 2], the 10% WTR specimens (9010) reach an average shear strength of 329 kPa and 2% WTR (982) specimens reach an average of 191 kPa. After one climatic (wet-dry WD) cycle [Test 3] the relationship between proportion of WTR and shear strength remains the same, however the strength reduces significantly for all soil types, e.g. peak of 59kPa for 10% amended WTR, which is an 82% decrease compared to the shear strength achieved after initial preparation of the specimens. There is slight further reduction in strength after 4 climatic cycles [Test 4], but most of the strength loss comes in one cycle. Interestingly, after a single climatic sequences, the co-amendment (9055 with 5% WTR and 5% compost) retains more strength compared to the WTR only amended soil specimens (green boxes in Fig. 3). This is also evident of specimens that have been through four wetting and drying cycles, and the co-amended soil retains the greatest long-term strength.

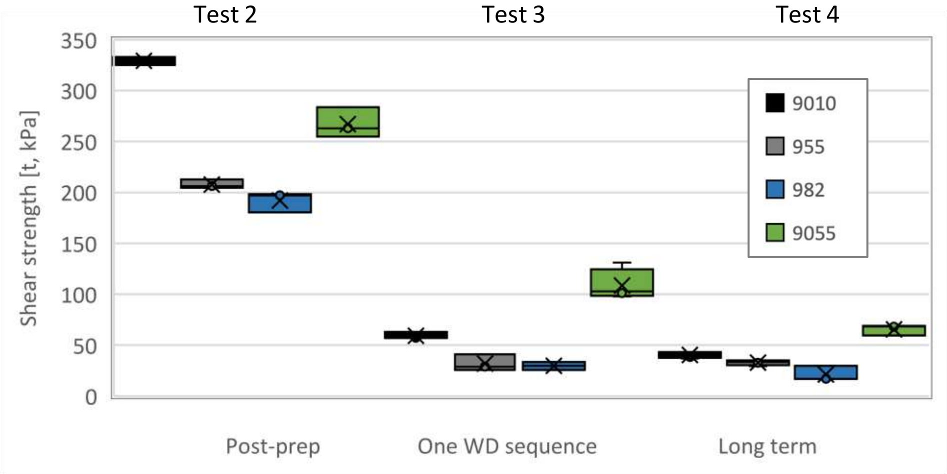
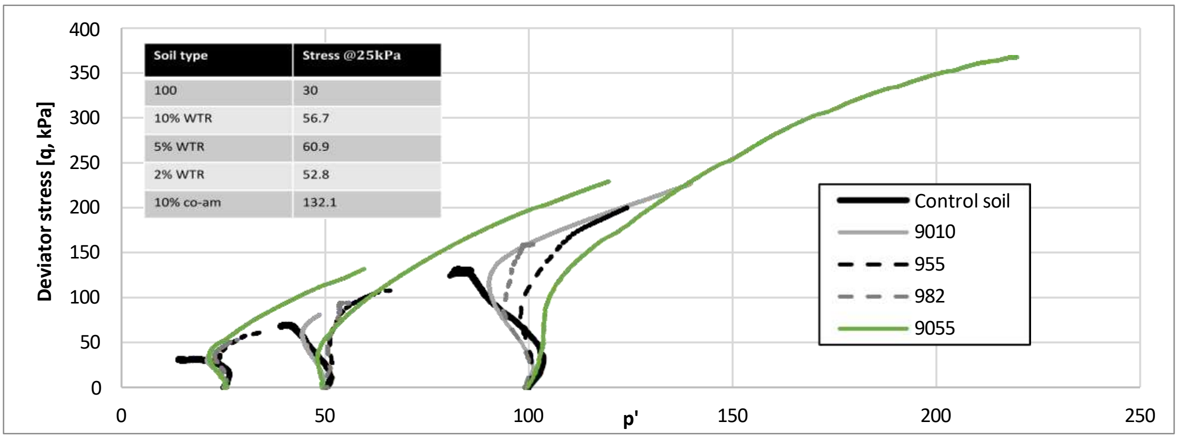


Figure 3: Comparison of shear strength values obtained immediately post preparation, after one wetting and drying cycle, and after four climatic cycles. The water content of all specimens is 0.31 g/g.

3.4 Consolidated Undrained Triaxial testing

Consolidated Undrained testing was carried out as multistage confined undrained triaxial tests on each soil type (n=3) as per BS 1377-8 (1990). Each specimen had been subjected to four wetting and drying cycles before testing and as such this test determines the long-term strength of amended remoulded soils.



Soil type	Stress @25kPa
100	30
10% WTR	56.7
5% WTR	60.9
2% WTR	52.8
10% co-am	132.1

Figure 4: Stress strain paths of a control soil compared to weathered WTR amended soils.

The stress paths in q-p' space are shown in Figure 4. Consolidated undrained triaxial testing of weathered WTR amended soils show that compared to the control soil, the stress path to the failure envelope is dilatant instead of contractant, allowing the soils to reach higher shear strengths. The control soil (sandy loam) is entirely contractant in nature at the prepared density, where positive changes in pore water pressure are produced in undrained conditions and the stress paths curve to the left. The addition of WTR of 2% (982), 5% (955) and 10% (9010) causes the soil to become more dilatant and as the soil approaches failure, the dilatant tendency causes a reduction in pore water pressure and the stress path turns to the right and climbs up the failure envelope, allowing greater strength to be generated. Interestingly, addition of greater WTR (5-10%) seems to suppress the early dilatant tendency to some extent, so the stress path is close to the control soil, but does dilate at higher strains. This trend is perhaps due to greater fine particles filling the voids of the control soil. The failure envelope does not change significantly due to the addition of WTR alone, and increases in strength are due entirely to dilatancy.

However, the addition of the co-amendment of 5% WTR and 5% compost (green lines in Fig. 4) shows a significantly greater dilatancy. In addition, the failure envelope for the co-amended soil is higher that that for the control soil and amended with WTR alone. Therefore, the co-amendment including WTR and compost shows significant benefits in terms of shear strength improvement.

4. Conclusions

The amendment of soil using a byproduct of water treatment (water treatment residual, WTR) has been previously shown to significantly improve the water holding properties of soil. The amended soil has the potential for use as a water holding layer in “climate adaptation composite barrier systems” to increase resilience to climate events. If such barriers are used for slope protection measures, to prevent landslides, then shear strength becomes an important consideration. It is shown that WTR amended soils need careful characterisation, as the compaction properties depend on whether the amended soil is prepared by wetting from a dry state, or drying from a wet state. The compaction testing completed shows that important considerations on the water content and preparation of amended soils are required if an amended material is to be used in civil engineering applications to make the most of the improved shear strength of amended soil.

The shear strength of amended soil was investigated by using both unconsolidated and consolidated undrained triaxial tests. Amending a sandy loam with between 2% and 10% WTR yielded significant improvements in shear strength, both immediately after preparation and after climatic cycles (drying and wetting). However, co-amendment of soil using 5% WTR and 5% compost achieved the greatest increase in shear strength.

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