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Properties of Hand-made Clay Balls used as a Novel Filter Media

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Abstract. Filtration using granular media such as quarried sand, anthracite and granular activated carbon is a well-known technique used in both water and wastewater treatment. A relatively new pre-filtration method called pebble matrix filtration (PMF) technology has been proved effective in treating high turbidity water during heavy rain periods that occur in many parts of the world. Sand and pebbles are the principal filter media used in PMF laboratory and pilot field trials conducted in the UK, Papua New Guinea and Serbia. However during first full-scale trials at a water treatment plant in Sri Lanka in 2008, problems were encountered in sourcing the required uniform size and shape of pebbles due to cost, scarcity and Government regulations on pebble dredging. As an alternative to pebbles, hand-made clay pebbles (balls) were fired in a kiln and their performance evaluated for the sustainability of the PMF system. These clay balls within a filter bed are subjected to stresses due to self-weight and overburden, therefore, it is important that clay balls should be able to withstand these stresses in water saturated conditions. In this paper, experimentally determined physical properties including compression failure load (Uniaxial Compressive Strength) and tensile strength at failure (theoretical) of hand-made clay balls are described. Hand-made clay balls fired between the kiln temperatures of 875°C to 960°C gave failure loads of between 3.0 kN and 7.1 kN. In another test when clay balls were fired to 1250°C the failure load was 35.0 kN compared to natural Scottish cobbles with an average failure load of 29.5 kN. The uniaxial compressive strength of clay balls obtained by experiment has been presented in terms of the tensile yield stress of clay balls. Based on the effective stress principle in soil mechanics, a method for the estimation of maximum theoretical load on clay balls used as filter media is proposed and compared with experimental failure loads.

Keywords: filter media; hand-made clay balls; firing temperature; compressive strength.

1. Introduction

The filter medium is "any material that, under the operating conditions of the filter, is permeable to one or more components of a mixture, solution or suspension, and is impermeable to the remaining components" (Purchas and Sutherland 2002). The principal role of the medium is to separate particulates from the liquid with the minimum consumption of energy. To achieve this, selection of the correct filter medium takes into account factors such as the particle sizes and their distribution,

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permeability of the clean medium, its particle retention capability and the permeability loss of the medium during use.

Pebble Matrix Filtration (PMF) is a pre-filtration method developed to protect slow sand filters from high turbidity usually encountered in surface waters during rainy periods (Rajapakse and Ives 1990, 2003, Rajapakse *et al.* 2005). PMF uses sand and pebbles as the filter media and the pebble-sand matrix helps to maintain a high permeability of the bed keeping a low head loss through the bed while filtering highly concentrated suspensions. The sustainability of this new technology might depend on availability and supply of pebbles and sand, both finite resources. In many countries there are two principal methods of obtaining pebbles and sand, namely dredging from rivers and beaches, and due to the scarcity of these resources in some countries the cost of pebbles is often 4-5 times higher than that of sand. In search for an alternative medium to pebbles after some preliminary laboratory tests were conducted in Colombo-Sri Lanka, Poznan-Poland and Cambridge-UK. A 100-year-old brick factory near Sudbury, Suffolk, UK has produced hand-made clay pebbles (balls) satisfying the PMF quality requirements (Rajapakse 2009).

A local brick company in Sri Lanka has produced few trial clay balls, but, after soaking in water for two weeks, the balls started to lose strength and even break up. One of such disfigured clay ball is shown in Fig. 1. Later it appeared that the brick factory did not control the temperature in the kiln during the firing process, and simply burnt these bricks at temperatures low enough to allow the workers to touch the bricks in the process. Although it is well known that differences in manufacturing methods give rise to differences in properties even when similar materials are used, and the local brick maker did not have access to such scientific information.

In order to increase the strength of clay balls and establish better firing conditions, two types of clay pebble were made in two different laboratories, fired at controlled temperatures and strength tests conducted before and after soaking in a water bath till saturation. The first type of clay pebble was made in the laboratory of a brick factory near Poznan (Laboratorium 'Cerabud', Krotoszyn), Poland and the second type was of white stoneware clay balls made and fired at the Cambridge Regional College, UK (Fig. 2).

As can be seen from the attached photo (Fig. 2), all of these clay balls made in the laboratory retained shape and strength before and after soaking in water till saturation. The details of strength tests conducted on these samples will be discussed later. Stoneware clay balls fired to 1250°C were nearly 5 times stronger than Polish clay balls which were fired at 960°C. It was also noted that both types of clay balls lost strength by 18% after soaking in water for 12 days, although the moisture absorbance was nearly 3.8 times higher in Polish clay balls compared to Stoneware clay balls at 12

Fig. 1 Disfigured Clay Ball (Sri Lanka)

Fig. 2 Brown, Poznan Clay Balls (Poland) White, Stoneware Clay Balls (UK)

(a) (b) (c) (d)

Fig. 3 Making Hand-made Clay Balls at Bulmer-Brick Factory, UK: (a) Making clay balls by hand at the 100-year old Bulmer Brick Factory in Suffolk, (b) Air drying, (c) Firing in kiln together with bricks, (d) Final product

days.

This paper presents mechanical properties of hand-made clay balls as a novel filter media. The variations of moisture absorption and the strength of hand-made clay balls with different types of clays and different firing temperatures are presented. The performance of the hand-made clay balls as novel filter media are then discussed.

2. Experimental: material testing

2.1 Ball preparation at bulmer brick & tiles using london clay

Having established a reliable procedure for making clay balls in the laboratory, a 100-year old brick company (Bulmer Brick & Tiles) was first approached to prepare some trial clay balls (48 mm diameter) from their own factory using London clay and then to produce them in sufficient quantity so that a filter column could be operated using these clay balls at a later stage. Three sets of trial clay balls were fired at three different temperatures; 875°C, 925°C and 950°C. As the trial clay balls had an average diameter of 48 mm, for the actual filtration column experiment the balls were made slightly bigger with an average diameter of 57.8 mm, and they were fired together with the bricks at Bulmer Brick & Tile Factory at a kiln temperature of 1100°C. The process of making the clay balls at the Bulmer Brick factory is shown in Figs. 3(a)-(d). The successful operation of a laboratory filter column using these London clay balls is described elsewhere (Rajapakse and Fenner 2011).

2.2 Physical properties of various hand-made clay balls

Granular filter media used in drinking water or wastewater treatment can have a wide range of physical properties, e.g., size range, density, porosity and shape. These variables characterise the media and define parameters for filtration performance prediction. In the case of granular filter media such as sand, anthracite or granular activated carbon (GAC) media size is usually referred to grain size and a grain size distribution is also given with an effective size (d_{10}). Also the density of the pebbles will have an implication on the cost of the structure. For example the density of natural pebbles would be much higher than that of clay balls; hence a PMF unit made of clay balls would be cheaper on the steel reinforcement. Furthermore, filter media may be subject to attrition during backwashing which will affect the grain size and porosity and the filter media must also be strong enough to resist the physical conditions involved during transport and placing media into filter beds and service. Sand and garnet, for example, are tough and usually present no problem. However, softer filtering materials such as clay balls are exposed to various conditions which could lead to breakage of the clay balls. Firstly, after manufacture the material is transported to the site in bulk, packed into boxes or bags and usually loaded on to pallets. Then, during the placing of filter media into the filters, people may tread on the clay balls. Finally, in the case of pebble matrix filtration, as the clay balls only acts as a stationary matrix within the filter box and the material at the bottom layers will be subjected to compression and shear due to self-weight and overburden it is important that clay balls in the lowest layer should be able to withstand these forces in water saturated conditions.

Although a friability test has been proposed (Humby *et al.* 1996) for bulk materials large enough to be sieved, at present there is no generally accepted test available for characterising the strength of the filter media such as clay balls in the context of their ability to withstand self-weight and other loads imposed during the life of the filtration process and service.

Taking into account all of these factors it was decided to evaluate some of the relevant physical parameters such as bulk density, moisture absorbance characteristics of clay balls, porosity of the clay ball matrix and compressive strength of dry and water saturated clay balls.

2.3 Moisture absorbance

The trial London clay balls were fired at three different temperatures, 875°C, 925°C and 950°C. The moisture (water) absorption of these clay balls were measured as a percentage increase in weight of water-soaked brick balls compared to dry brick balls, and measurements were taken starting 30 minutes onwards until saturation moisture content was reached.

2.4 Strength characteristics

The Uniaxial Compressive Strength (UCS) is undoubtedly the most often quoted geotechnical property that is commonly used in rock engineering practice, The point load test (PLT) is another test to measure the rock strength index (Rusnak and Mark 2000) by compressing a rock sample between conical steel platens until failure occurs. The mechanics of the PLT actually causes the rock to fail in tension and the accuracy in predicting the UCS therefore depends on the ratio between the UCS and the tensile strength (Hoek 1977). The point load test (PLT) was not conducted on clay balls as the apparatus was not readily available; however, it is an alternative to the UCS because it can provide similar data at a lower cost and worth considering in future tests.

The UCS was used to ascertain the strength of the various clay balls and then compared with the crushing strength of natural Scottish cobbles. In this method individual clay balls were placed between the two parallel plates of the compression test rig and load applied till failure as shown in Figs. 4(a)-(c). The purpose of the strength test was to ensure that these clay balls made under laboratory conditions have sufficient strength to withstand their own weight within the filter and in soaked conditions. Accordingly, the balls were first tested in dry conditions and then soaked in water to saturation point and tested again to check whether there was any deterioration in strength due to soaking. The moisture content of the soaked clay balls was also calculated by weighing the dry and wet samples.

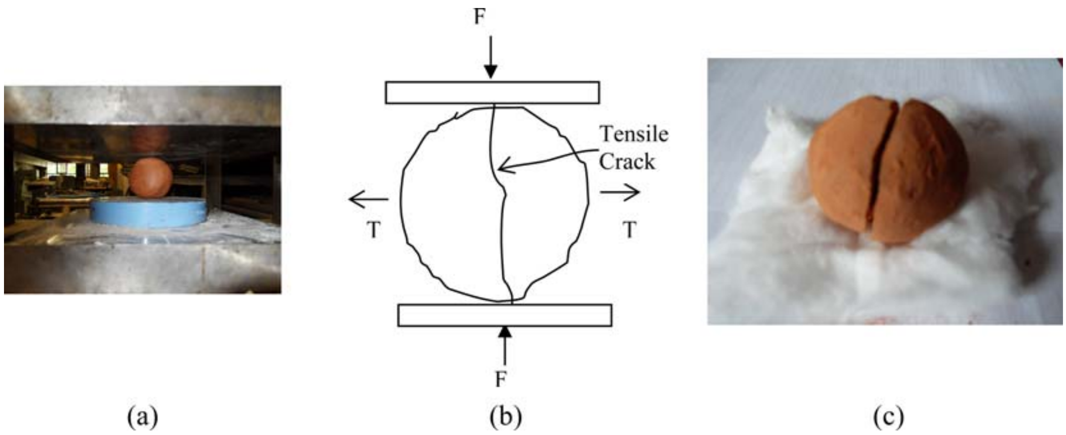


Fig. 4 Compression testing of clay balls: (a) UCS testing, (b) Mode of failure, (c) Failed sample

3. Results and discussion

3.1 Moisture absorption of fired clay balls

Dry density of London clay balls were 1600-1700 kg/m^3, whereas Polish clay balls and Cambridge Stoneware clay balls had higher values of 1880 kg/m^3 and 2270 kg/m^3 respectively. Natural Scottish cobbles had the highest density of 2500 kg/m^3. Only the dry bulk density of London clay balls fired at 1100°C was evaluated to be of 850 kg/m^3 as these were produced in large quantities and used in filtration column studies (Rajapakse and Fenner 2011). With maximum water absorption of 16%, the saturated bulk density of these balls would be 1360 kg/m^3. The saturation moisture content was

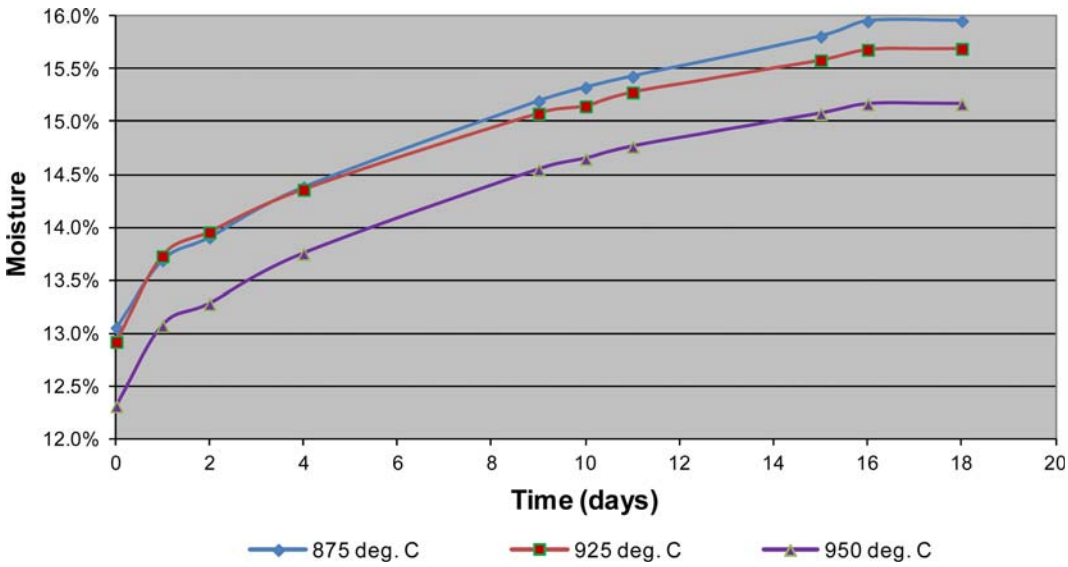


Fig. 5 Moisture absorbance with time of clay balls fired at different temperatures (London clay balls)

reached at around 16 days (Fig. 5).

As can be seen from Fig. 5, all of the tested London trial clay balls with three different firing temperatures had moisture contents between 12.3%-13.0% after 30 minutes of soaking and reached a saturation value of between 15.2%-15.9% after 16 days. Each graph represents the average value of three clay balls. It is also evident that moisture absorbance pattern of clay balls fired at 875°C and 925°C were somewhat similar and absorbed about 4-5% higher moisture content compared to balls fired at 950°C. The reason may be due to slight reduction in porosity as a result of fusion of clay particles at higher temperatures.

In Table 1 below, the water absorption and compressive strength properties of bricks by various National Standards together with some reported data (AIT 2003) of factory made and country made bricks from India are given for information. From this table it appears that there is no direct relationship between water absorption and compressive strength and the Australian Standards even does not indicate any limit on the water absorption.

Furthermore it should be noted that among other factors the compressive strength of bricks are affected by the aspect ratio (height: width) and orientation of the specimen during testing, and generally conducted by imposing a compression load on the bed face of the brick until failure, and the 'crushing' or compressive strength is calculated simply as the stress at failure based on the transverse cross-sectional area. In the case of clay balls, they were placed between the two parallel plates of the compression test rig as shown in Fig. 4. In this case an indirect measure of the brick ball's tensile strength resulted from tensile stresses in terms of the cross-section in a plane containing the load axis, due to compressive loading is calculated. This indirect measurement of tensile strength test is sometimes known as the 'Brazillian', or 'diametral compression' test.

Table 1 Water absorption and compressive strength properties of bricks

Code	Class	Compressive strength (min.) (N/mm^2)=(MPa)	Water absorption (max) % By mass
British standards BS 3921: 1985	Engineering A	70	4.5
	Engineering B	50	7.0
	Damp proof 1	5	4.5
	Damp proof 2	5	7.0
	All other	5	No limit
Australian standards AS 1225: 1984	Height: width $\leq$ 0.7	7	No limit
	Height: width $\geq$ 2.0	5	No limit
American standards ASTM C 62-89a	Severe weathering	20.7	17
	Moderate weathering	17.2	22
	Negligible weathering	10.3	No limit
Singapore standards SS 103 : 1974	Grade 1	35	25 (common bricks)
	Grade 2	20	
	Grade 3	5.2	
India (AIT 2003)	Country made (1750-1850 kg/m^3)	2.0-2.4	15-20
	Factory made (1850-1900 kg/m^3)	7.8-10.8	13-15

The density of bricks can vary from 1300 kg/m^3 to 2200 kg/m^3, depending on the raw material used and manufacturing process (Ali 2005), and directly influence the weight of the structure. Therefore compared to for example natural Scottish cobbles with a density of 2500 kg/m^3, the use of clay balls with a density of 1700 kg/m^3, the savings on reinforcement on the structure would be quite significant.

3.2 Strength of fired clay balls and natural Scottish cobbles

A summary of the various laboratory tests conducted on different clay balls with failure loads are given in the Table 2 below.

Frocht and Guernsey (1952) analysed the photoelastic test results of an elastic sphere of diameter d loaded at its poles by a force F and found that the tensile stress normal to the vertical plane passing through poles distributes fairly uniformly over the centre part, about half the diameter wide, and takes the value from 2.4 to 2.8 times $F/\pi d^2$. The similar results were reported by Harimatsu and Oka (1966) from the analysis of their photoelastic experiments on an elastic sphere loaded at its poles.

The analysis conducted by Frocht and Guernsey (1952) expressed the compressive stress acting normally at the centre of the equatorial plane, Z, and the maximum tensile stress acting normally at the centre of the polar plane, T, by Eqs. (1) and (2), respectively.

$$Z = 3.30\frac{F}{d^2} \tag{1}$$

$$T = 0.573\frac{F}{d^2} \tag{2}$$

Table 2. Laboratory strength tests of various clay balls vs. Natural scottish cobbles (average of 3 samples)

Material of sample	Kiln temp	Dry density (kg/m^3)	Water absorption (%)			UCS (kN) tested at (*)	
			12 days (*)	18 days (*)	31 days (*)	Dry	Soaked till (*)
Natural scottish cobbles (51.6 mm)	n/a	2500	0.4%	-		29.5	25.8
Cambridge stoneware trial clay balls (51.5 mm)	1250ºC	2270	3.2%	-		35.0	28.7
	Air dried for 2 weeks (not fired)					0.8	
Polish trial clay balls (51.0 mm)	960ºC	1880	12.1%	-		7.1	5.8
London trial clay balls (48.1 mm)	875ºC	1700	-	16.0%		3.0	3.2
	925ºC	1700	-	15.7%		4.3	3.7
	950ºC	1660	-	15.2%		3.5	3.4
London clay balls used in filter (57.8 mm)	1100ºC	1675			15.8%	5.1	5.1 (*) 98 days

Using Eqs. (1) and (2), T can be expressed in terms of Z as follows

$$T = 0.1737\ Z \tag{3}$$

Sternberg and Rosenthal (1952) derived that the compressive stress, Z, acting normally across the centre of the equatorial plane of a spherical aggregate loaded at its poles by a force, F

$$Z = \frac{6F}{\pi.d^2}\left(\frac{14+5\mu}{7+5\mu}\right) \tag{4}$$

Where, d *is* the aggregate diameter and μ is the Poisson ratio.

When the polar loading force, F, is equal to failure load of the sphere (F_f), the tensile yield strength of the material, T_s, will be given by the combination of Eqs. (3) and (4).

$$T_s = \frac{0.3317F_s}{d^2}\left(\frac{14+5\mu}{7+5\mu}\right) \tag{5}$$

Bakhteri *et al.* (2004) has recommended using Poisson's ratio of 0.25 for fired clay bricks. Using this value for Poisson's ration, the tensile yield strength (T_s) of clay balls can be calculated from Eq. (6).

$$T_s = 0.613\frac{F_s}{d^2} \tag{6}$$

The effective diameter, d, in Eq. (6) for reasonably spherical aggregates of larger than 5 mm, it was proposed to measure the longest (d_x), intermediate (d_y) and smallest (d_z) diameters of each particle of the aggregate and the average d, calculated by

$$d = \frac{d_x + d_y + d_z}{3} \tag{7}$$

For aggregates with the shape of an ellipsoid, with principle diameters d_x, d_y and d_z, the effective spherical diameter was calculated using formula

$$d = (d_x d_y d_z)^{1/3} \tag{8}$$

The tensile yield strength at failure (T_s) using Eq. (6) for dry and water saturated material with different firing temperatures (where applicable) are given in Table 3.

From this table it appears that the natural Scottish cobbles had the highest tensile strength at failure (over 5000 kPa) and air dried (not fired) Stoneware clay balls had the smallest value of 197 kPa, but increased this value nearly 40 fold to above 7716 kPa after firing to a temperature of 1250°C. This may be due to fusing of clay particles through a process known as 'vitrification of clay' at higher temperatures as observed in ceramic and pottery industry. In ceramic or pottery making clay is heated to a point at which it is physically and chemically changed and cannot return to its raw state. There are two firing stages called 'Bisque (biscuit)' and 'Glost (or glaze)'. Before the bisque, or biscuit, firing clay must be bone-dry, or 'leather-hard' to avoid cracking or exploding in the kiln due to any water still held in the clay trying to find its way out. At leather-hard the free water is already lost and some shrinkage has occurred; only the chemically-bound water remains. This is driven off by a slow rise in temperature up to around 500°-550°C. The rate of bisque firing

Table 3 Tensile yield strength (T_s) at failure using Eq. (6)
(#) single sample, all others average of 3 samples

Material & average size of sample	Kiln temp	Tensile yield strength (T_s) at failure (kPa)			
		Dry sample	Soaked in water for 12 days	Soaked in water for 18 days	Soaked in water for 98 days
Natural scottish cobbles (51.6 mm)	n/a	5583	5267	–	–
Cambridge stoneware trial clay balls (51.5 mm)	air dried for 2 weeks (not fired)	197 (#)	–	n/a	–
	1250°C	7716	7093	–	–
Polish trial clay balls (51.0 mm)	960°C	1578	1504	–	–
London trial clay balls (48.1 mm)	875°C	775	–	771	–
	925°C	1145	–	968	–
	950°C	935	–	916	–
London clay balls used in filter (57.8 mm)	1100°C	947	–	–	932

is relatively slow up to 550°C then faster up to top temperature. A glaze firing is unlike bisque in that the rate of climb in temperature is consistent, after a short slow start to drive off any water left from glazing. During glazing (also known as 'vitrification') the spaces between refractory particles are completely filled up with glass, fusing the particles together and making the clay body impervious to water. It may be possible that the Poznan clay balls were bisque fired to a temperature of 960°C giving a T_s value of 1578 kPa, while Stoneware clay balls 1250°C reached vitrification with a T_s value of 7716 kPa. As can be seen from Fig. 6, the T_s of dry London clay balls increases from 775 kPa at 875°C to 1145 kPa at 925°C and then decreases to 935 kPa at 950°C. Increasing the temperature beyond this point up to 1100°C had no effect on the T_s value.

The existence of an optimum firing temperature for clay from Beruas (Malaysia) on compressive

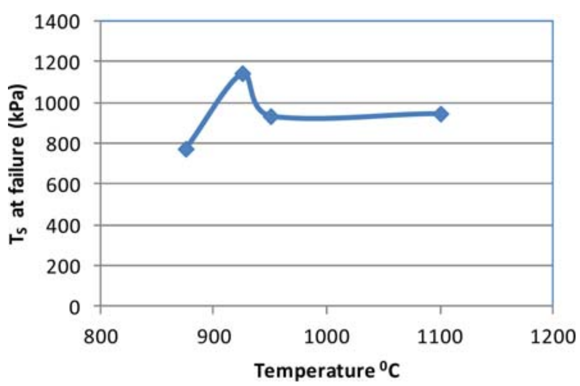


Fig. 6 Effect of firing temperature on T_s (London clay)

strength of bricks has also been reported by Johari *et al.* (2010). As reported by Andam (1990), the temperature at which vitrification takes place is specific to every clay sample, however, in practice clay samples from the same deposit may be regarded as having a similar optimum firing temperature at which vitrification would occur. The London clay balls fired to a temperature of 1100ºC and used in filter column retained a T_s value of 932 kPa after 98 days soaking in a water bath, only 1.6% reduction from the original T_s of dry balls.

All of the samples fired at or above 875ºC maintained a high tensile strength whether they were dry or soaked in water till saturation, which is an essential property of a filter medium.

3.3 Durability of clay balls

The durability of clay balls and more importantly the required annual replacement rate of clay balls in full scale operation would be an important parameter the asset owner may be interested to know. Generally, compressive strength alone does not necessarily offer useful information regarding brick durability and it is considered to be closely related to the degree of vitrification, together with lower porosities and favourable pore size distributions resulting an enhanced durability (Elert *et al.* 2003). However, after the laboratory testing of over nearly hundred days no single clay ball appeared to have deteriorated in quality or sustained any form of damage, yet this important aspect need to be investigated further in full scale studies. With brick on the great wall of China dating back to 300 BC and 'Jetavanaramaya Stupa' in Sri Lanka (built in 273-301 AD using 93 million fired bricks at 120 m high) both structures open to all weather conditions, bricks are well known to be durable having life expectancy of hundreds of years.

4. Estimation of theoretical maximum load on clay-balls by effective-stress principle

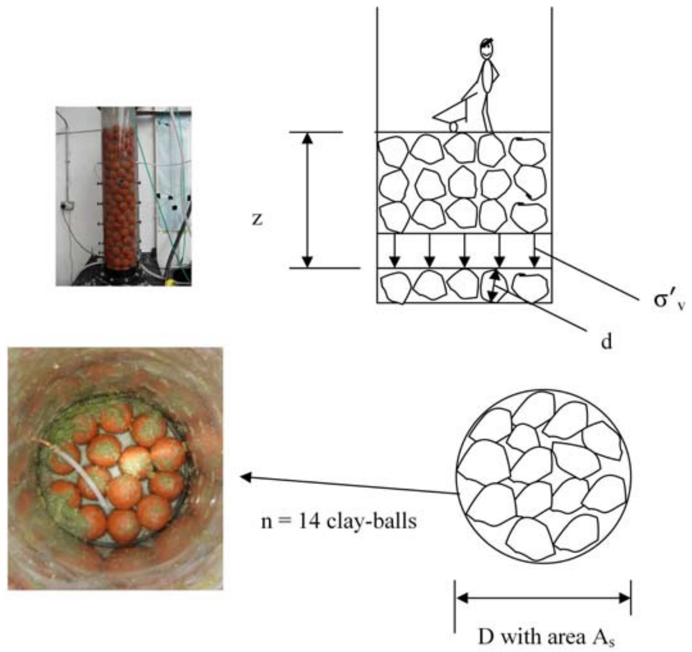
The calculation assumes that the voids in the total depth of clay ball matrix is filled with sand and saturated with water. In addition a surcharge of 2 people (200 kg)/m^2 was added to represent the overburden during installation and maintenance works. The hypothesis is that if the bottom layer of clay-balls is strong enough to withstand the load above that layer, then all other balls in the bed will not be crushed due to self-weight of the bed.

Based on the effective-stress principle applied to Fig. 7

$$\sigma_v' = (\gamma_{sat}^{matrix})z - u \tag{9}$$

Where;

σ_v' = Effective stress
γ_w = Unit weight of water = 10 kN/m^3
u = Pore water pressure = $\gamma_w\, h_w$ = 10 × 1 = 10 kN/m^2
V^{matrix} = total volume of the matrix = 0.051 m^3
γ_{sat}^{matrix} = Saturated unit weight of clay ball matrix filled with sand
γ_{sat}^{ball} = 17 × 16% (using higher density of 1700 kg/m^3 & 16% moisture)
= 19.72 kN/m^3
V^{ball} = total volume of clay balls within matrix
= (number of balls within matrix) × (volume of one ball)



Z = about 1.0 m; D = 0.255 m; d = about 58 mm

n = 14 (No of clay balls on bottom layer)

Fig. 7 Application of effective stress principle to pebble matrix during construction

$$= \left[14\frac{1.0m}{0.058m}\right] \times \left[\frac{4}{3}\pi\left(\frac{0.058}{2}\right)^3\right]$$

$= 0.025\ \text{m}^3$

W_{sat}^{ball} = weight of saturated clay balls = 0.025 m^3 × 19.72 kN/m^3
= 0.493 kN

W^{sand} = weight of sand occupied within pores of the 1.0 m high matrix
= 31.68 kg (by experiment) × 10/1000 = 0.3168 kN

Therefore, true volume of sand occupied within matrix:

V^{sand} = 31.68/2650 = 0.012 m^3 (assuming sand specific gravity = 2.65)

V^{water} = volume of water within matrix = ($V^{matrix} - V^{ball} - V^{sand}$)
= (0.051-0.025-0.012) = 0.014 m^3

W^{water} = weight of water within matrix = 0.014 m^3 × 10 kN/m^3 = 0.14 kN

Therefore, the weight of the saturated clay ball matrix filled with sand;

$$W_{sat}^{matrix} = W_{sat}^{balls} + W^{sand} + W^{water}$$

$= 0.493 + 0.3168 + 0.14 = 0.9498$ kN

Add surcharge of 2 kN/m^2 (2 people/m^2) gives, Therefore, the total saturated weight of the matrix

$= 0.9498$ kN + (2 kN/m^2 × filter area)
$= 0.9498$ kN + (2 kN/m^2 × 0.051 m^2)
$= 1.052$ kN

and,

$\gamma_{sat}^{matrix} = 1.052$ kN/ 0.051 m^3 = 20.62 kN/m^3
$\sigma_v' = 10.62$ kN/m^2

For bottom-layer of clay balls to withstand load above that layer

$$\sigma_v' \cdot A_s = F_{Total} \le f \cdot n \tag{10}$$

Where

A_s = Column cross sectional area with diameter D
f = Effective load on each clay ball

From Eq. (10) above

$$f = \frac{\sigma_v' . A_s}{n} = \frac{10.62 \times \pi \times (0.255)^2}{14 \times 4} = 0.04 \text{ kN}$$

The failure load of saturated London clay balls in the compression test was in the range of 3.2-3.7 kN, showing a very high safety factor.

5. Conclusions

Based on the contents of this paper and the experiments conducted, the following conclusions can be drawn

- In the absence of natural pebbles, hand -made clay balls made of naturally abundant locally available materials can be manufactured to required specification using local labour and firing together with bricks to minimize embodied energy. Clay balls fired to a temperature of 850°C or above can provide sufficient strength to be used as a filter media, although the optimum firing temperature for strength may be higher. Energy can be saved at lower temperatures.
- Uniaxial Compressive Strength (UCS) test provided a suitable method for establishing the compressive strength of hand-made clay balls. The clay balls fired up to 950°C achieved a saturated moisture content of 15-16% after soaking 18 days in water, and lost strength between 0-14% compared to dry balls. Clay balls fired to a temperature of 1250°C were nearly 40 times stronger than air dried balls, and lost strength by 18% after soaking in water for 12 days. The uniaxial compressive strength of clay balls obtained by experiment has been presented in terms of the tensile yield stress (T_s) of clay balls.
- The effective stress principle showed that the load on clay balls is very small compared to strength of clay balls achieved after firing.
- With continuing innovations in the manufacturing process the energy requirements of making

bricks are becoming more efficient. The traditional brick-making industry in many developing countries is a provider of vast employment, using indigenous technology and there is the spin-out potential for setting up clay ball production as a micro enterprise. Hence, clay balls are not only an effective and a practical alternative to natural pebbles but a sustainable solution with environmental and economic benefits.

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