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Strength properties of composite clay balls containing additives from industry wastes as new filter media in water treatment

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Abstract. Pebble matrix filtration (PMF) is a water treatment technology that can remove suspended solids in highly turbid surface water during heavy storms. PMF typically uses sand and natural pebbles as filter media. Hand-made clay pebbles (balls) can be used as alternatives to natural pebbles in PMF treatment plants, where natural pebbles are not readily available. Since the high turbidity is a seasonal problem that occurs during heavy rains, the use of newly developed composite clay balls instead of pure clay balls have the advantage of removing other pollutants such as natural organic matter (NOM) during other times. Only the strength properties of composite clay balls are described here as the pollutant removal is beyond the scope of this paper. These new composite clay balls must be able to withstand dead and live loads under dry and saturated conditions in a filter assembly. Absence of a standard ball preparation process and expected strength properties of composite clay balls were the main reasons behind the present study. Five different raw materials from industry wastes: Red Mud (RM), Water Treatment Alum Sludge (S), Shredded Paper (SP), Saw Dust (SD), and Sugar Mulch (SM) were added to common clay brick mix (BM) in different proportions. In an effort to minimize costs, in this study clay balls were fired to 1100°C at a local brick factory together with their bricks. A comprehensive experimental program was performed to evaluate crushing strength of composite hand-made clay balls, using uniaxial compression test to establish the best material combination on the basis of strength properties for designing sustainable filter media for water treatment plants. Performance at both construction and operating stages were considered by analyzing both strength properties under fully dry conditions and strength degradation after saturation in a water bath. The BM-75% as the main component produced optimum combination in terms of workability and strength. With the material combination of BM-75% and additives-25%, the use of Red Mud and water treatment sludge as additives produced the highest and lowest strength of composite clay balls, with a failure load of 5.4 kN and 1.4 kN respectively. However, this lower value of 1.4 kN is much higher than the effective load on each clay ball of 0.04 kN in a typical filter assembly (safety factor of 35), therefore, can still be used as a suitable filter material for enhanced pollutant removal.

Keywords: pebble matrix filtration; composite clay balls; material combinations; uniaxial compression test

1. Introduction

Accessibility to safe water is one of basic human rights, where any contamination of water is highly vulnerable on human health. Primary water sources are exposed to a great risk, particularly

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in highly populated zones due to human factors which can profoundly impair water quality and hence increasing the vulnerabilities to waterborne diseases. Deforestation, large scale farming, climate change, and rapid urbanization result in pollutants such as high levels of nutrients, pathogens, NOM and highly turbid water containing high sediment loads discharging into water courses during rainy periods (Raspati *et al*. 2013, Wright *et al*. 2013). Filtration with granular materials such as quarried sand, pebbles, granular activated carbon and anthracite has been the common media typically used to remove suspended particles, microbes and other pollutants in both surface and ground water sources.

Pebble matrix filtration (PMF), a pre-filtration method developed to protect slow sand filters from high turbidity and rapid head loss has been found to be effective (Rajapakse and Ives 2003) both in the laboratory and in field trials. Selection of suitable filter material for PMF, especially for a rural water treatment process is challenging due to local availability of both natural pebbles and sand with the required particle sizes and distributions (Rajapakse *et al*. 2012). Hand-made clay pebbles (balls) are an alternative to natural pebbles in terms of their low cost and environmental sustainability, especially for rural water treatment plants where natural pebbles are not locally available. The use of mono-medium clay balls as a new filter media has been tested in the laboratory (Rajapakse 2011, Rajapakse and Fenner 2011) and the strength properties of clay (alone) balls have been discussed in an earlier publication (Rajapakse *et al*. 2012). A new composite filter media has been developed to improve the pollutant removal efficiency in terms of NOM and turbidity in water treatment. Research conducted by Cheeseman and Virdi (2005) has indentified lightweight, water absorption, and crushing strength as important properties of pebbles when using them as filter media.

The present study investigates the strength properties of composite clay balls when common brick clay (Brick Mix) was further mixed with additional raw materials to extend the pollutant removal ability for NOM removal in addition to turbidity. However, only the strength properties of composite clay balls are described here as the pollutant removal is beyond the scope of this paper.

Performance of hand-made clay balls under soaking conditions during the filtering process depends on some critical factors such as material type, burning temperature, burning conditions, and packing conditions (Rajapakse *et al*. 2012). The handling process of clay balls in large scale filters further affects the durability of filter media, where live loads by vehicle and human movements on top of clay balls layer during the construction stage creates significant impacts for crushing and breaking up clay balls. The strength of clay balls should be able to sustain such live loads and dead load by self-weight of the upper layers during construction stage of PMF. It has been observed that clay balls (without additives) fail in tension when they are loaded (Rajapakse *et al*. 2012). In this study, the effects of material combinations and their quantities as composite clay balls on the strength were investigated. In addition to the strength of individual clay balls the stability of the filter bed against local shear failure is also an important factor to be studied using direct shear tests, but will be outside the scope of this paper.

2. Experimental program

Two different schemes were proposed to investigate the performance of clay balls for water treatment plants:

(1) Effects of different material combinations, and
(2) Effects of different material quantity as shown in Fig. 1

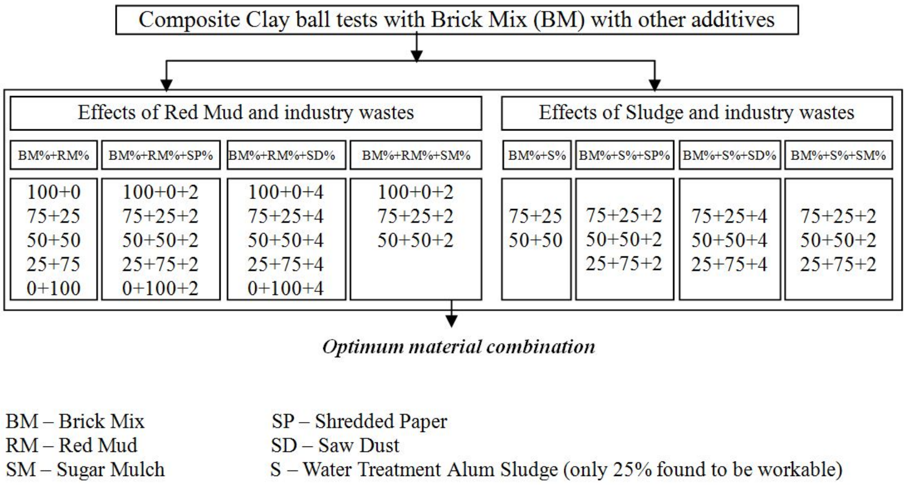

Fig. 1 Experimental program for investigation of composite clay balls for PMF

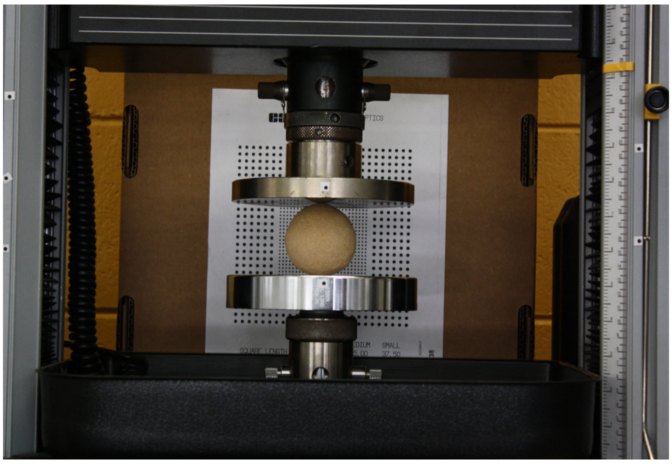

Fig. 2 Typical test set-up

These combinations were tested in both fully dry and saturated conditions, using uniaxial compression strength (UCS) test as shown in Fig. 2, (which has proved as a suitable measure for evaluating tensile strength of clay balls; Rajapakse *et al*. 2012). After measuring the diameter of clay balls in three different planes to compute their mean effective diameter, all specimens in this study were crushed in a 50 kN Instron machine applying load with a constant deformation rate of 0.2 mm/s to quantify the polar strength distribution of each ball. Material characteristics of BM, RM and S are given in Figs. 3 and 4. The average strength of three balls was used to represent one individual strength value.

2.1 Material used

Due to the additional benefit of their pollutant adsorption properties (Wendling 2008), Red

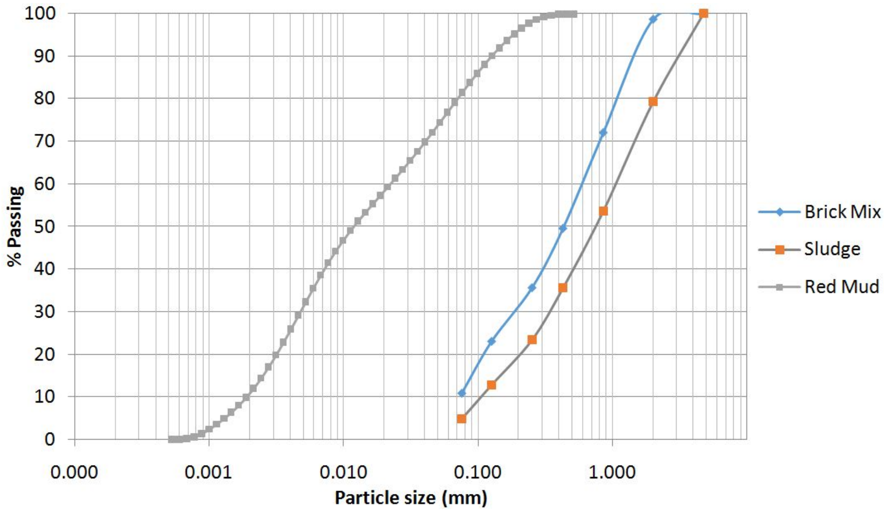

Fig. 3 Particle size distributions of raw materials

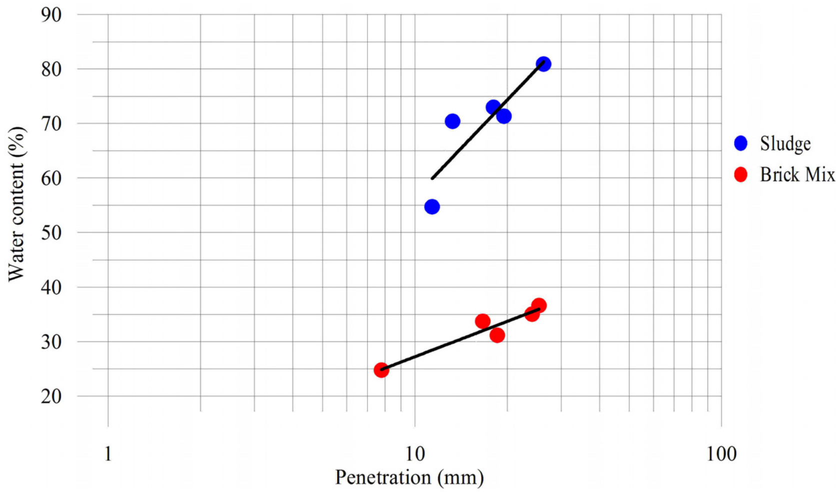

Fig. 4 Liquid limit test results for raw materials

Mud (RM) and Water Treatment Alum Sludge (S) were introduced to the brick mix in five different proportions. Another three different industry wastes; 2% of shredded paper (SP), 4% of saw dust (SD), and 2% of sugar mulch (SM) were further introduced at different combinations to brick mix with red mud and sludge to enhance porosity (USEPA 1999) of the finally burnt clay pebble products. The 25 different combinations using red mud, sludge, & other three industry wastes with brick mix were tested to evaluate the UCS of the composite clay balls. In an effort to minimize costs, in this study clay balls were fired to 1100°C at a local brick factory together with their bricks. These balls were crushed to quantify the degradation of the clay pebble strength after the saturation process. The mass of both dry and wet clay balls were used as a key factor to observe the water content and the rate of saturation of balls.

However, the results of a previous study by Rajapakse *et al*. (2012) showed that clay balls fired at 800°C provided sufficient strength for water treatment applications at both construction and operational stages and no strength degradation at soaked conditions were noticed. Clay balls soaked in a water bath for at least 35 days was assumed sufficient to fully saturate them and replicate the state of clay balls in a water treatment plant during its operational stage.

The particle size distribution of material used for clay balls affects other key parameters such as permeability, density, and compressibility. Particle size distributions of Red Mud, Brick Mix and Sludge obtained according to ASTM 1253.12 2006 are shown in Fig. 3. Atterberg limits define the boundaries between material consistency states, which are basic measurements of critical water contents of fine grained materials. Liquid limit for both brick mix and sludge were estimated as 34% and 75% respectively, using cone penetration liquid limit test results shown in Fig. 4. Following ASTM 1253.123.2004, the plastic limits of the brick mix were estimated as 16.4%. According to the unified soil classification system (USCS), brick mix can be classified as “SP-SC, Poorly graded clayey sand”.

2.2 Sample preparation

All three main materials: brick mix, red mud, and sludge used for clay balls preparation were less than 4.75 mm (passed through no.4 sieve). The dimensions of other industry wastes used for composite clay balls preparation were 5 mm × 50-100 mm for shredded papers and 50-100 mm long for sugar mulch. Preparation of clay balls with specific diameter is however one of the critical tasks due to the effects of shrinkage in the drying and burning processes of the clay balls. After several trials to overcome such effects of shrinkage, correct material mass portions for preparing

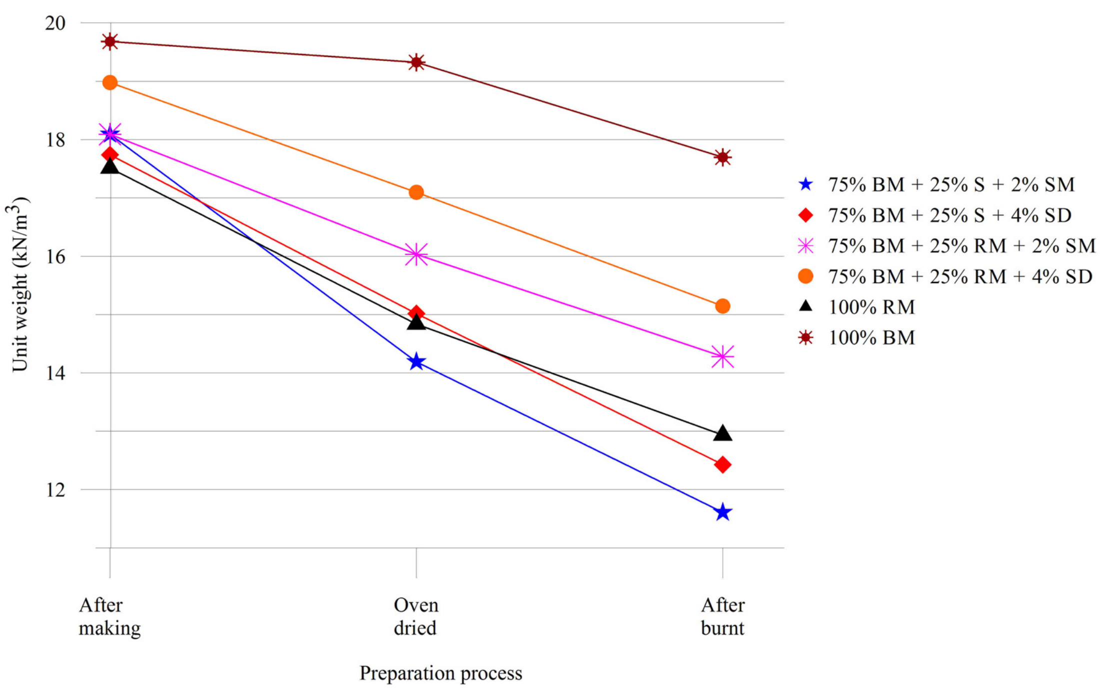

Fig. 5 Unit weight variation within balls preparation process

clay balls with different material combinations were estimated to obtain nearly equal sizes for each pebble. In this clay ball preparation process, adequate workability was achieved to form dough using the main materials and industry wastes, through adding water only for main material mixture. In order to establish the unit weight variation during the ball preparation process, some wet clay balls were prepared by rolling this dough with hand-palms, ensuring an even shape and next, placed these wet clay balls in the room temperature for four days, before oven drying under about 60°C-70°C for 24 hours. Variation of the unit weight of clay balls in each preparation step were as follows: just after rolling, oven dried, and after burning (as illustrated in Fig. 5). The final unit weight of clay balls after the burning process only with the brick mix, significantly changes due to adding red mud, sludge, and industry wastes as shown in Fig. 5. Addition of Alum Sludge reduces the burnt unit weight of clay balls by nearly 18% compared to red mud. Further, by adding 2% of sugar mulch or 4% of saw dust, the burnt unit weight can further reduce by 6%. Density is an indicator of cost of water treatment plants, where low density material for PMF results lower cost on reinforced concreted base of treatment plant (Rajapakse *et al*. 2012). Fig. 5 shows that the addition of sludge makes the balls with low density and this agreed with work of Chiang *et al*. (2009) where water treatment sludge was used to manufacture lightweight bricks. In this research, 75%BM +25%S+ 2%SM is the best option for water treatment, due to its lower burnt unit weight. The strength of such clay balls should be however strong enough to resist conditions due to transporting, placing, and backwashing (Rajapakse *et al*. 2012).

3. Laboratory experiments and results

3.1 Effects of the addition of Red Mud (RM) and Alum Sludge (S) to Brick Mix (BM)

To enhance the pollutant removal properties, two additional materials: red mud and sludge were introduced for composite clay pebble preparation. Nine combinations were investigated by changing portions of different materials as shown in Fig. 6. The two combinations: 25%BM + 75%S and 100%S were not considered for this investigation giving consideration to the recommendations made by Elangovan and Subramanian (2011). In a laboratory study by Elangovan and Subramanian (2011), alum sludge was used as a partial substitute in clay bricks to a maximum of 20% without compromising the strength of the bricks. Ramadan *et al*. (2008) also used water treatment alum sludge with weight ratios from 50% to 80% sludge-clay mixture and concluded that 50% was the optimumsludge addition to produce brick from sludge-clay mixture. In another study in Egypt, Hegazy *et al*. (2012) used water treatment alum sludge (S), silica fume (SF) and rice husk ash (RHA) in different proportions by weight for brick making and concluded that 50(S):25(SF):25(RHA) produced best brick properties superior to the 100% clay control-bricks and to those available in the Egyptian market.

Introducing red mud and sludge into the brick mix reduces the maximum polar strength of clay balls at all combinations, except for the 25%BM + 75%RM combination. After adding 75% of red mud into the brick mix, the maximum polar strength increases by 23%. However by replacing the brick mix totally by red mud the strength reduces dramatically by 87% from a maximum polar strength of 100% brick mix clay balls. Adding red mud into the brick mix undergoes higher deformation to reach its maximum polar strength compared to pure brick mix clay balls. The 75%BM + 25%RM combination however reduces strength by 7% whilst simultaneously showing significant deformation under loading conditions before reaching its maximum capacity. A study by Dodoo-Arhin *et al*. (2013) in Ghana found that 50%-50% red mud-clay composite bricks produced best combination with optimal properties for the construction bricks application. However, 20-30% clay content also produced bricks that could be used in lightweight structural applications.

With the addition of 25% and 50% of sludge to BM can lower the strength of clay balls by 78% and 98% respectively as shown in Fig. 6. The balls with 50% sludge combination are not suitable as a filter material since the balls simply crumbled with the slightest impact with other balls. However, it is important to note that with the 25% sludge, the failure load of 1.4 kN is still much higher than the effective load on each clay ball of 0.04 kN in a typical filter assembly as shown in previous studies (Rajapakse *et al*. 2012), therefore, can be safely used as a suitable filter material. With such high factor of safety although one might argue whether these rigorous strength tests are necessary in the first place, without conducting these tests it would not be possible to make such conclusions as no previous research has been done with composite clay balls of this nature. For example the 75%sludge + 25%BM combination does not appear to satisfy strength criteria as a filter material at all as they were already crumbled in the oven. With regard to RM, 75%BM + 25%RM combination is the suitable material combination to ensure higher polar strength capacity and deformation under experienced loads at both construction and operating stages of water treatment plants.

3.2 Effects of the addition of industry wastes

With the purpose of improving porosity (after firing) within composite clay balls, three industry wastes were further introduced in three different percentages: 2% of shredded paper, 4% of saw

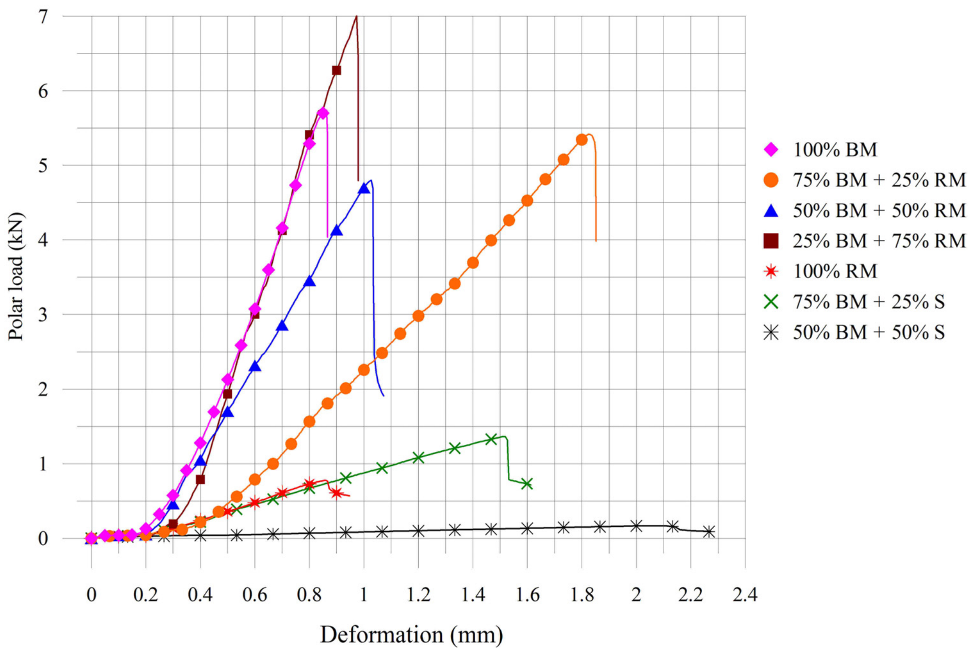

Fig. 6 Effects of red mud and sludge on pebble strength

dust, and 2% of sugar mulch. This paper only considers the influence of these three industry wastes on selected material combinations with raw materials from above section as 75%BM + 25%RM and to evaluate their influence on sludge, 75%BM + 25%S combination. After introducing these three industry wastes for 75%BM + 25%RM combination, the maximum polar strengths of new clay balls significantly reduce as illustrated in Fig. 7. 2% of shredded paper, 4% of saw dust, and 2% of sugar mulch degrade the strength of clay balls by 28%, 42%, and 56% respectively even under totally dry conditions as shown in Fig. 7. Deformation characteristics of these new combinations significantly decrease compared to conditions at without industry wastes, introducing sudden failures due to lower polar strength and further degradation under soaked conditions. 2% of shredded paper is the best alternative compared to other two options due to its lower strength degradation at dry conditions. A key disadvantage of using these industry wastes in composite clay balls, these wastes can be burnt under higher burning temperature, introducing surface impurities, and holes inside the balls. These holes can increase the permeability of the clay pebble layer by enhancing the efficiency of water filtering process, however resulting in lower strength capacity. The irregular polar strength distribution of 75%BM + 25%RM + 2%SM clay balls set in Fig. 7 could be due to the breaking of sugar mulch fibres with the increase of loading.

As can be seen in Table 1, the behavior of industry waste with sludge is slightly different from performance with red mud. As with red mud after introducing industrial waste, the maximum polar strength degrades by 23%, 42%, and 67% due to 4% of saw dust, 2% of shredded paper, and 2% of sugar mulch respectively from 75%BM + 25%S combination as shown in Fig. 8. Further, deformability of clay balls increases when adding industrial waste to 75%BM + 25%S combination. When burning clay balls at a temperature of 1100°C, industrial waste such as saw dust, shredded paper, and sugar mulch added to 75%BM + 25%S could be burnt out creating voids inside clay balls. These voids could contribute for larger deformation and lesser ultimate polar load compared

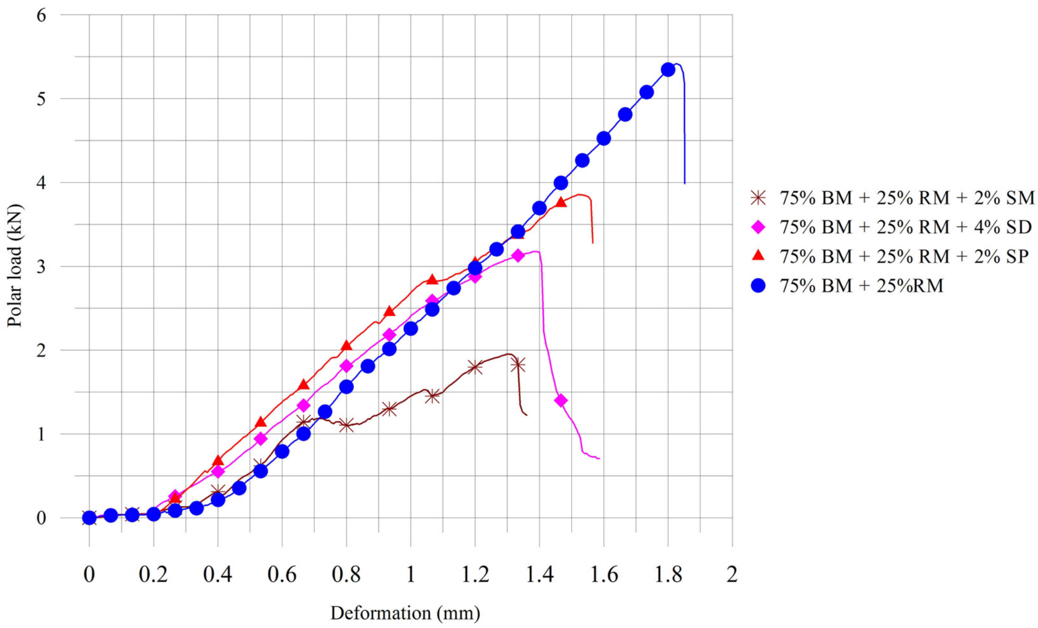

Fig. 7 Effects of industry wastes with red mud on balls strength

to those of 75%BM + 25%S combination.

3.3 Moisture absorption characteristics of burnt clay balls

The behavior of clay pebble strength characteristics at the construction and operating stages are critical to maintain properly functioned water treatment plants, when using clay balls as filter

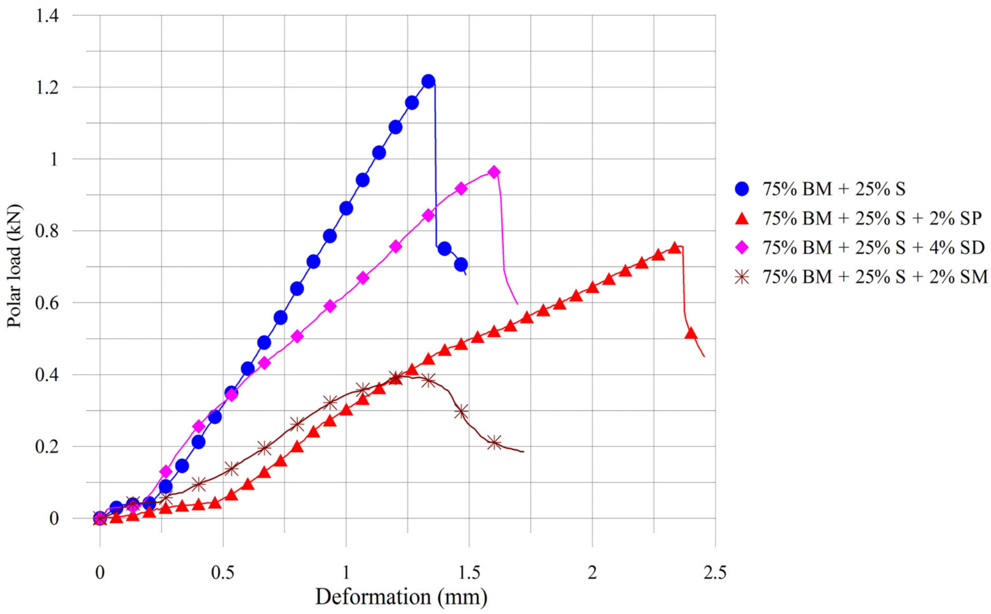

Fig. 8 Effects of industry wastes with Sludge on ball strength

Table 1 Effect of industrial wastes as additives for brick mix and red mud

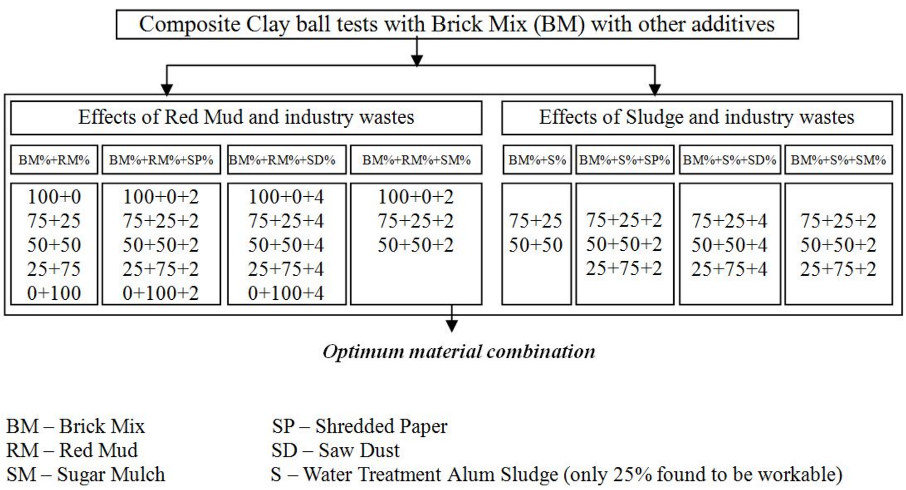

Fig. 1 Experimental program for investigation of composite clay balls for PMF

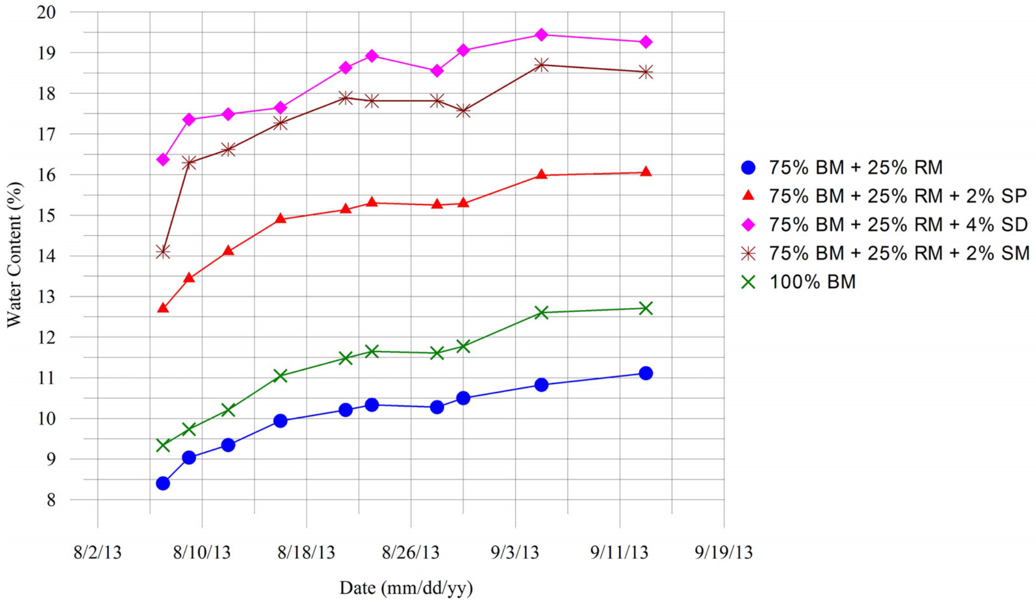

Fig. 9 Water content variations of clay balls

material. Though dry strength characteristics are the governing factors at the construction process of water treatment plants, soaked strength characteristics control the performance of operating process. Early investigation concluded that strength of clay balls degrade under soaking conditions, resulting sudden failures mostly due to material washing (Rajapakse *et al*. 2012). To evaluate the influence of soaking conditions, five different clay balls with different material combinations were soaked until achieving fully saturated conditions and these fully saturated clay balls were crushed to understand the influence of soaking conditions on strength degradation.

Fig. 9 illustrates water content variations of fully dried clay balls, after placing in a water bath for 35 days. These clay balls were oven dried for three days under 110°C to ensure zero moisture inside balls, before starting to place in water bath for measuring water content of balls. The masses of clay balls, after cautiously removing surface water were measured for 35days to obtain fully saturated clay balls. 75%BM +25%RM clay balls show the lowest moisture absorption, while it is a maximum in 75%BM + 25%RM + 4%SD clay balls as illustrated in Fig. 9. The possible reasons to have such a higher moisture absorption in 75%BM + 25%RM + 4%SD clay balls can be higher moisture absorption capacity of saw dust and hole/impurities caused by the burnt saw dust. The work by Chemani and Chemani (2012) using saw dust as a pore-forming agent for clay brick making showed that saw dust can be added up to 9% by weight with optimum results and without compromising mechanical properties of the bricks. The moisture absorption capacity of industry wastes increases from shredded papers to saw dust. Clay balls with industry wastes further showed a higher absorption rate compared to clay balls only with raw materials due to the higher porosity of composite clay balls with industry wastes. Viruthagiri *et al*. (2013) used saw dust to increase porosity in insulating bricks so that the presence of porosity would decrease the thermal conductivity of the insulating bricks. They concluded that the porosity of the bricks could be controlled by varying the percentage saw dust mixture up to 20% without compromising compressive strength.

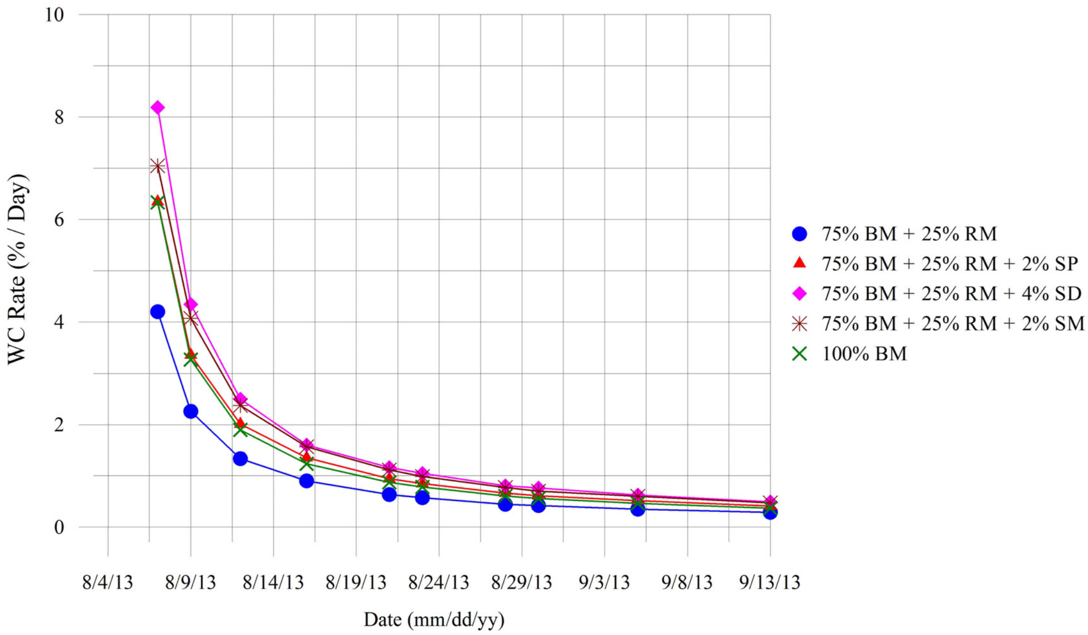

Fig. 10 Water absorption rate variations of clay balls

In designing water treatment plants using clay balls, water absorption rate is important to determine the load applying rate on lower layers and stress applied on inner surface of treatment plant by volume changed compared to water content of clay balls. Fig. 10 illustrates the water absorption rate of five different clay balls under soaking process. Unfortunately within this experimental program, volume change of clay balls with moisture absorption rate was unable to measure. According to Fig. 10, water absorption rates between 100%BM and 75%BM + 25%RM + 2%SP clay balls are identical, and 75%BM + 25%RM + 2%SM and 75%BM + 25%RM + 4%SD clay balls further show similar variation with each.

3.4 Effects of mositure on strength of clay balls

Only three different clay balls with different material combinations were considered to evaluate the influence of soaked process on degradation of clay balls strength as shown in Fig. 11. Only 75%BM + 25%RM + 2%SP clay balls were considered to evaluate the impacts of clay balls saturation on strength degradation since this combination shows higher performance compared to others with industry wastes. The maximum strength of 100%BM clay balls decreases by 24% and maximum deformation decreases from 1.32 mm to 0.97 mm. Such degradation of both strength and deformation of saturated clay balls can introduce early failure mechanism than dried balls. The maximum polar strength of the 75%BM + 25%RM clay balls under fully saturated conditions surprisingly increases more than in dry conditions by 16%, however the maximum deformation of balls reduces from 1.83 mm to 1.77 mm as shown in Fig. 11. Influence of strength degradation of 75%BM + 25%RM + 2%SP for saturated clay balls is negligible in term of both maximum strength and deformation of balls. 75%BM + 25%RM therefore is the best material combination to overcome strength degradation effects under saturation process.

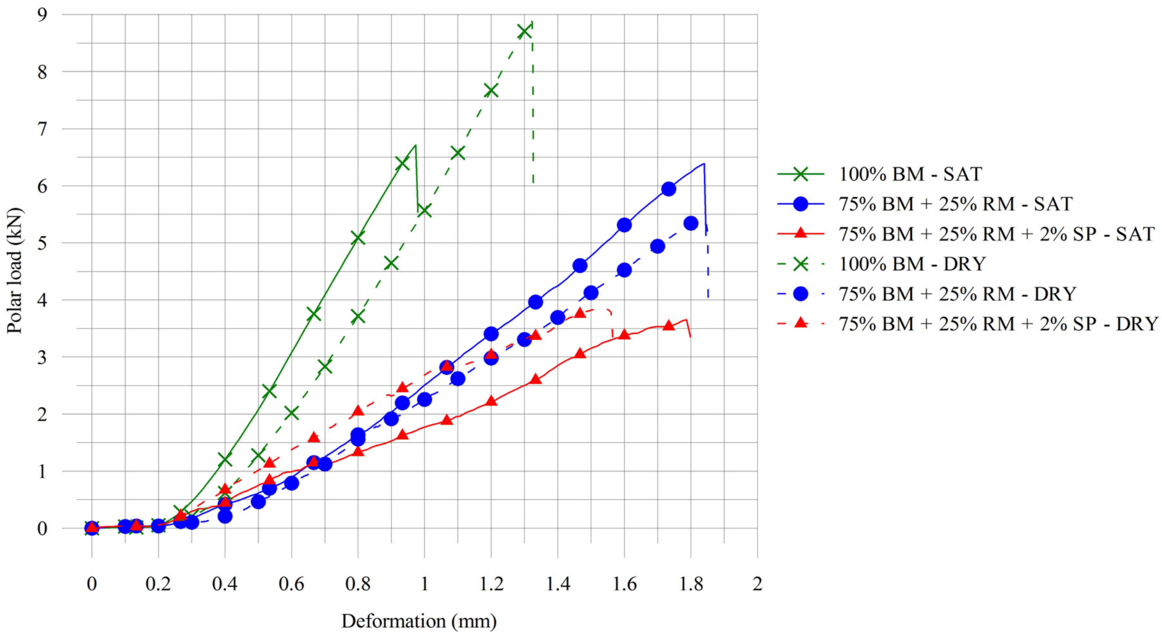

Fig. 11 Effects of moisture on strength of clay balls

4. Conclusions

The following conclusions were derived based on the analysis of experimental results:

- Clay balls made of the combination of Brick Mix (BM), Red Mud (RM), and Alum Sludge (S) were tested for the polar strength. The polar strength was significantly decreased by adding sludge and it can be recommended to use the maximum of 25% of sludge when making balls to have enough strength for them to survive during filter construction.
- Three different industry wastes (saw dust - SD, shredded papers - SP, sugar mulch - SM) were introduced to clay mixes (e.g., 75%BM + 25%RM and 75%BM + 25%S) to quantify their influence on crushing strength of composite clay balls. It was observed that the polar strength and the stiffness of the clay mix decreased by adding the industry waste. The lowest polar strength and the stiffness were recorded for 75%BM + 25%S + 4%SM. This combination achieved the polar strength of 0.4 kN which still gives facto of safety of 10 against the crushing during the filer construction. The water absorption of burnt clay balls made of 100%BM, 75%BM + 25%RM, 75%BM + 25%RM + 2%SP, 75%BM + 25%RM + 4%SM, and 75%BM + 25%RM + 2%SD were tested and found that water absorption was significantly increased by adding industry waste. The highest water absorption was observed for 75%BM + 25%RM + 4%SD.
- When comparing the polar loads of dry and saturated clay balls made of 100%BM, 75%BM + 25%RM, and 75%BM + 25%RM + 2%SP, as expected the saturation decreased the dry polar load by about 20% except for 75%BM + 25%RM whose saturated polar load is slightly greater than that of dry.

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