Estimation of Poisson's ratio and variation of tensile yield strength of composite clay balls used in pebble matrix filtration

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Abstract: Clay balls can be used as alternatives to natural pebbles in pebble matrix filtration, a device for drinking water treatment. These clay balls are subjected to stresses due to self-weight and overburden in water saturated conditions. Although there are empirical relationships for evaluating tensile yields strength (Ts) of clay balls using Poisson's ratio (μ), diameter (d) of clay balls, and failure polar force (Fs), so far for such calculations the value of Poisson's ratio (μ) was taken from studies based on clay bricks. However, during ball preparation if clay is mixed with other raw materials from industry wastes such as saw dust or alum sludge in order to enhance the pollutant removal properties of the filter media, then the Poisson's ratio (μ) of composite balls would be quite different to that of clay bricks. This paper describes a novel method for estimating Poisson's ratio (μ) of composite clay balls by measuring vertical deformation using linear variable displacement transducers (LVDTs) in uniaxial compressive strength (UCS) apparatus and lateral deformation using particle image velocimetry (PIV).

Keywords: *Composite clay balls, Poisson ratio, PIV, Tensile yield strength, Pebble Matrix Filtration, Filter media*

Introduction

Pebble matrix filtration (PMF), a pre-filtration method for high turbidity removal of surface waters has found effective both in the laboratory and in field scales (Rajapakse and Ives 1990; Rajapakse and Ives 2003; Rajapakse et al. 2005; Rajapakse and Fenner 2011; Rajapakse et al. 2012). Selection of suitable filter material for PMF, especially for a rural water treatment process is challenging due to local availability of natural pebbles and sand with required particle sizes and their distributions. Hand-made clay pebbles (balls) is an alternative to natural pebbles in filter media in terms of low cost and environmental sustainability, especially where natural pebbles are not readily available. The use of mono-medium clay balls as a new filter media has been tested in the laboratory (Rajapakse and Fenner 2011) and the strength properties of mono-medium clay balls have been discussed in Rajapakse et al., 2012. To further enhance the pollutant removal ability of these clay balls which were made of clay, a material known as brick mix (BM), some waste materials such as saw dust, red mud, water treatment alum sludge, shredded paper, and sugar mulch were added to the BM at various proportions (Rajapakse et al. 2015). The strength properties of these composite clay balls were evaluated using uniaxial compression test.

Pressure and viscous (drag) force due to flow, gravity and uplift forces however impose on the filter media (Indraratna and Radampola 2002). 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 under saturated conditions. Rajapakse et al. (2012) highlighted that the tensile yield strength (Ts) of clay pebbles should provide a factor of safety against self-weight and overburden pressure of the PMF. Sternberg and Rosenthal (1952) developed an expression to evaluate tensile yield strength (Ts) of clay pebbles using Poisson's ratio (μ), diameter (d), and failure polar force (Fs) as given in Eq 1. During the compression test, the strength of a clay ball depends on the tensile strength in a cross sectional plane along the loading axis. The maximum tensile strength was defined as the tensile yield strength of a clay ball. Compression force (Polar force) was an indirect measurement of the tensile strength of a clay ball during testing. The maximum polar force was defined as the failure polar force in this study.

$$T_S = \frac{0.3317\, F_S}{d^2}\left(\frac{14+5\mu}{7+5\mu}\right) \tag{1}$$

The value of Poisson's ratio of clay pebbles however were based on the clay bricks in estimating the tensile yield strength in the previous studies. Although the Poisson ratio of clay bricks may be taken as approximately similar to the mono-medium clay balls, when clay is mixed with other additives, the composite clay balls would not have the same properties as mono-medium clay balls. In this study, UCS apparatus was used for crushing clay balls and vertical deformation was measured using both linear variable displacement transducers (LVDTs) and particle image velocimetry (PIV), whereas lateral deformation was measured using particle image velocimetry (PIV) only. After establishing a good correlation between the vertical LVDT and the PIV measurements, the results were used to calculate Poisson's ratio of composite material in tensile yield strength test under the uniaxial loading conditions.

Laboratory Experiments

Lateral Deformation Measurement using PIV

In recent years, digital image correlation method became more applicable in non-contact deformation measurements (Pan et al. 2009). Due to higher cost in contact deformation measurements of the composite clay balls in lateral direction, the PIV method, which was originally developed for measuring velocity of fluids (Adrian 1991) and later modified for evaluation of natural soil particle movement (While and Take 2002), was used in this study. This method was implemented to analyse the image sequence and it quantifies the development of volumetric and shear strains within the interface shear zone (Westgate and DeJong 2006). The PIV analysis procedure summarized by Hosseini et al. (2014) was followed here. Application of the GeoPIV software developed by White and Take (White et al. 2003) in analyzing digital images in the PIV method for strain calculation was highlighted by Bandula-Heva and Dhanasekar (2011) and the use of the GeoPIV is described in detail by Madabhushi (2014).

For the PIV analysis, the composite clay balls were tested under monotonic loading conditions at a constant displacement rate (1mm/min) to ensure static loading requirements. Fig. 1 illustrates the experimental setup used for measuring lateral strain of the composite clay pebbles. Digital images of clay pebbles were taken every five seconds (0.20Hz), using a canon EOS 450D computerized camera under consistent camera settings; appropriate continuous light intensity, camera shutter speed, and zero manual intervention of camera. Both time-load history, time-displacement history under the UCS test conditions and time-digital image history under the PIV test conditions were obtained for each composite clay balls during the loading.

Digital images taken at a constant time interval from beginning to yield point were used for the PIV analysis to evaluate lateral strain of composite clay balls. Fig. 2 shows the grid of patches of an input digital image developed in the PIV analysis, with a typical size of a patch as 120 × 120 pixels. Based on the investigations of White et al. (2003), the precision error, ρ_{pixel}, can be calculated using following equation:

$$\rho_{pixel} = \frac{0.6}{L} + \frac{150{,}000}{L^8} \tag{2}$$

Where, L is patch size. Here, error is 0.0005 pixels, which is less than standard error of 0.0007 pixels (Hosseini et al. 2014). Size of grid, patches, and distance between patches depends on the requirement of analysis and quality of digital images. Both vertical and lateral strains were evaluated in this study, adopting the method proposed by Bandula-heva and Dhanasekar (2011) and Thamboo et al. (2013). Key critical task of this analysis however was to minimize the error by 3-D effects of clay pebbles in calculating plane strain in the PIV analysis. Previous PIV studies were associated only with plane strain elements such as square and rectangular blocks (Bandula-heva and Dhanasekar 2011; Thamboo et al. 2013). To minimize these effects, two precautions were taken as follows: 1) in calculating vertical strain, two reference points were introduced to each loading plate of uniaxial compression apparatus as shown in Fig. 2 and vertical strain of clay pebbles were determined using these four reference points, 2) in calculating horizontal strain, reference patches along neutral axis (diameter) were selected for calculation.

Comparison of deformation measured using LVDT and PIV method

Fig. 3 illustrates the comparison of vertical strain calculated using the PIV method and experiments results from the USC test using the LVDT for different three clay balls. Elasticity behavior of specimens in Test 2 and Test 3 shows a similar behavior as same material type used in these two experiments with two different pebble sizes, where Test 3 has a higher diameter than Test 2 experiencing higher time for crushing as shown in Fig. 3. Materials used in Test 1 are altered from Test 2 & Test 3, resulting a diversion of elastic behavior from Test 2 and Test 3. According to Fig. 3, vertical strain values calculated using the PIV analysis method shows a minor deviation with experimental strain values obtained from USC test results. The fluctuation of the PIV vertical strain values in Fig. 3 from experimental strain values may be as a results of uncertainties associated with experimental conditions such as light intensity and humidity, defects in digital camera, and uncertainties in the PIV analysis. Considering this good agreement in vertical strain values shown in Fig. 3, the PIV method was used in remaining analyses in this paper to evaluate the lateral strain of the composite clay pebble materials in Poisson’s ratio calculation.

As the PIV method is suitable to evaluate vertical and lateral strain of composite clay pebbles, these two strain values were calculated for each composite clay pebble type. Fig. 4 illustrates the distribution of vertical strain and lateral strain of a typical composite clay pebbles and Poisson's ratio of clay pebbles were evaluated using these distribution. Key reasons for some scattered points in distribution between vertical and lateral strain values are uncertainties in the PIV analysis and the test environment as explained earlier and the impurities in hand-made clay pebbles, especially with those made with three industry wastes.

Strength Characteristics Analysis

Tensile yield strength Measurement

According to Sternberg and Rosenthal's (1952), tensile yield strength of a ball is a function of failure polar force, Poisson's ratio and ball diameter (Eq. 1). An experimental setup was proposed in this study to evaluate the validation of this expression on the clay pebbles, prior to estimate the tensile yield strength of the composite clay pebbles. With same constant Poisson's ratio, the tensile yield strength can be simply estimated using the slope of failure polar force verses square pebble diameter distribution as given in Eq. 3, which is a rearranged version of Eq. 1.

$$F_s = \left(\frac{7+5\mu}{.0331*(14+5\mu)}\right) d^2 T_s \tag{3}$$

Fig. 5 illustrates the variation of failure polar force with square diameter of five clay ball types with different diameters, which were built using only brick mix (BM) soil. Poisson's ratio of these clay balls should be equal since it is not a function of physical characteristics of clay balls. This variation between failure polar force and square diameter provides a better agreement with conditions discussed in Eq. 3. The tensile yield strength of 100% brick mix clay pebbles is 145kN/m^2, according to Fig. 5. Fluctuation of points in Fig. 5

may be results of uncertainties associated with the PIV analysis and the controlled experiment environment. Since there is a negligible diversion, this proposed method for estimating the tensile yield strength of the composite clay pebbles is used in this paper.

Effects of Burning Temperature

Burning temperature of the clay pebbles is a critical factor, which maintains long-term performing of water treatment process at service stage. Rajapakse et al. (2012) discussed the influence of burning temperature on failure polar force of composite clay pebbles. Fig. 6 illustrates the tensile yield strength distribution under different burning temperatures of composite clay pebbles with 50mm diameter. Previous studies (Rajapakse et al., 2012) also showed that clay balls burnt at a temperature of 850 ^{0}C and above can provide sufficient strength to be used as filter media. The tensile yield strength reduces by nearly 54% when burning temperature increased from 800 ^{0}C to 1000 ^{0}C, while it dramatically increases by approximately 287% after a 100^{0}C burning temperature increment from 1000^{0}C as shown in Fig. 6. It is possible that cracks may have developed in clay balls due to various reasons, such as excess water content. These cracks could serve as weak joints within clay balls and rupture through these cracks early during testing, whereas, when balls were fired beyond 1000^{0}C complete vitrification takes place increasing the tensile yield strength. The effect of additional materials on tensile strength is shown in Figures 7-11. Sludge is non-plastic weaker material compared to BM and RM. So adding Sludge to BM, the tensile yield strength of BM-Sludge mixture can be much less than BM+RM as shown in Figure 7. Tensile yield strength of BM (100%) decreases by adding RM. RM increases the elastic properties of BM that could reduce the Tensile strength (Figure 8). Adding industry wastes to BM or the mixture of BM-RM, the tensile yield strength decreases as it increase the voids in the ball after burning at high temperature. Often, the tensile yield strengths of saturated (wet) balls are slightly higher than those of dry balls. Curing the balls in water can enhance the cementitious bonding between particles to increase the tensile strength of balls (Figure 10).

Effects of Additional Materials

Fig. 7 illustrates the influence of additional materials: red mud (RM) and sludge (S) added with brick mix soil as the first step to make the composite clay pebbles in this study with 50mm diameter and 800^0C burning temperature. After introducing these two additional materials, the tensile yield strength of the mono-medium brick mix clay pebbles decreases with portion increment of additional material as given in Fig. 7. The tensile yield strength gradually reduces with red mud portion until adding 50% of red mud into the mono-medium brick mix clay pebbles, where the tensile yield strength changes from 1354 kN/m^2 to 1086 kN/m^2 nearly by 20%. After further adding extra 25% of red mud into 50% red mud clay mixture, the tensile yield strength enhance by 67% from 1086 kN/m^2 as shown in Fig. 7. With totally replacing brick mix by red mud with same similar diameter and burning temperature, the tensile yield strength of clay pebbles reduce from 1354 kN/m^2 to 170 kN/m^2 by 88 percentage.

Impact of sludge on brick mix in clay pebble's tensile yield strength is critical compared to influence of red mud, where even after adding 25% of sludge to brick mix, the tensile yield strength reduces from 1354 kN/m^2 to 249 kN/m^2 by 82%, while after adding 50% of red mud, it reduces by 20%. Further increase of sludge percentage becomes significant since the tensile yield strength reduces by 98% after adding 50% of sludge into brick mix soil as shown in Fig. 7. Due to such reduction, influence of 75% and 100% sludge with brick mix in the tensile yield strength is not considered in this study. Considering facts as higher tensile yield strength and lower clay pebble preparation cost, soil mixture of 25% of brick mix and 75% of red mud is the best material proportion for composite clay pebbles.

Effects of Industry Wastes

In second stage of the composite clay pebbles preparation, three different industry wastes: 2% of shredded paper, 4% of saw dust, and 2% of sugar mulch were introduced. This new material mixture modification allows enhancing the sustainability of the composite clay pebbles in the water treatment process in the slow sand filters. Fig. 8 shows the impacts of induced industry wastes on the tensile yield strength of the mono-medium brick mix clay pebbles and the composite clay pebbles with brick mix and red mud. The tensile yield strength of the mono-medium brick mix clay pebbles reduces with the industry wastes as 55%, 37%, and 78% for shredded paper, saw dust, and sugar mulch, respectively, as shown in Fig. 8. Due to lack of the material availability of sugar mulch, only three different composite clay pebbles with sugar mulch were tested in this study. Influence of rest of the industry waste materials in 100% red mud on the tensile yield strength is negligible. After introducing 2% of shredded paper into brick mix and red mud soil mixture, the tensile yield strength of these composite clay pebbles gradually decreases as in Fig. 8. The tensile yield strength of clay pebbles reduce from 1354 kN/m^2 to 1124 kN/m^2 after introducing 25% of red mud into 100% brick mix soil, however after adding 2% of shredded paper into above two clay pebble materials, the tensile yield strength of clay pebbles increase from 618 kN/m^2 to 853 kN/m^2 respectively. 75% of the tensile yield strength reduction surprisingly appears in clay pebbles with 25% brick mix and 75% red mud through an addition of 2% of shredded paper.

Impact of saw dust in clay pebbles shows an opposite behavior compared to shredded paper, where reduction pattern of the tensile yield strength of both composite clay pebbles with brick mix and red mud soil mixture and after adding 4% of saw dust has a similar behavior as illustrated in Fig. 8. After mixing 4% saw dust, the tensile yield strength decreases by 37%, 34%, 8%, and 18% in composite clay pebble with 0%, 25%, 50%, and 75% red mud proportion, respectively. Influence of sugar mulch in the tensile yield strength has totally separated performance compared to both shredded paper and saw dust, where after adding 2% of sludge mulch for brick mix and red mud soil mixture, the tensile yield strength regularly increases with portion of red mud in the composite clay pebbles as in Fig. 8. This impact on the tensile yield strength is however insignificant compared to the influence caused by shredded paper and saw dust. Concerning all these facts, best material proportion for composite clay pebbles with red mud and industry wastes is 25% brick mix, 75% red mud with 4% saw dust.

As shown in Fig. 7, sludge creates a significant impact on the tensile yield strength and only three different composite clay pebbles were prepared due to such higher strength reduction. To evaluate the influence of industry wastes in composite clay pebbles with sludge, shredded paper, saw dust, and sugar mulch were introduced for soil mixtures and evaluated the tensile yield strength of each clay pebble group as illustrated in Fig. 9. The tensile yield strength of clay pebbles decreases by 44%, 26%, and 68% after adding 2% of shredded paper, 4% of saw dust, and 2% of sugar mulch into the composite clay pebbles soil mixture with 25% sludge and 75% brick mix. The influence of these three industry wastes in 50% sludge and 50% brick mix soil mixture can be negligible as given in Fig. 9.

Detailed analysed results of Fig. 7, Fig. 8, and Fig. 9 describe the impacts of red mud, sludge, and three different industry wastes: shredded paper, saw dust, and sugar mulch on the composite clay pebble with brick mix soil. Best suitable sustainable material proportion for the composite clay pebbles for the preliminary water treatment in slow sand filters is 25% brick mix and 75% red mud with 4% saw dust due to its higher tensile yield strength, lower cost, and lower environmental pollution.

Effects of Moisture in Composite Clay Pebbles

Long-term performance of the composite clay pebbles as preliminary treatment process in water treatment plants with the slow sand filters depends on performance in both construction and operating stages. Strength characteristics of hand-made clay pebbles can significantly affect under soaking conditions, according to past experience in Sri Lanka (Rajapakse et al. 2012; Rajapakse 2011). To estimate the influence of moisture on the tensile yield strength of the composite clay pebbles, the tensile yield strength of clay pebbles estimated under fully saturated conditions soaked for 35 days. Fig. 10 and Fig. 11 illustrate the variation of the tensile yield strength of clay pebbles under fully dried and saturated conditions with red mud and sludge, respectively. Impact of moisture on the tensile yield strength of the composite clay pebbles with 100% red mud, 2% sugar mulch in all material proportions, 50% brick mix-50% red mud with all industry wastes, 25% brick mix-75% red mud without any industry waste is negligible, according to Fig. 10.

The tensile yield strength reduces by 6% and 11% in 100% brick mix and 4% saw dust (100% brick mix) clay pebbles correspondingly under the fully saturated conditions. After introducing shredded paper for 100% brick mix clay pebbles, strength however enhances by 30% under fully saturated conditions compared to fully dry tensile yield strength and similar behaviour shows with 25% brick mix-75% red mud with same industry waste as shown in Fig. 10. As expected with moisture, the tensile yield strength of clay pebbles with 25% brick mix-75% red mud with 4% saw dust still reduces from 1486 kN/m^2 to 1299 kN/m^2

by 13 percent. 2% of shredded paper wastes show a better performance compared to other industry wastes since it can enhance the tensile yield strength characteristics of hand-made clay pebbles under soaking conditions, which is more valuable in water treatment process, where strength reduction is a serious problem in long-term performance. 25% brick mix-75% red mud with 4% saw dust are still having 52% higher tensile yield strength than 25% brick mix-75% red mud with 2% shredded paper, even after 13% strength reduction under soaking conditions.

To evaluate the influence on moisture in the tensile yield strength degradation process of clay pebbles with sludge, only 75% brick mix-25% sludge clay pebble type was examined in this study since the tensile yield strength of 50% brick mix-50% sludge clay pebble, even under fully dry condition is negligible as in Fig. 7. Composite clay pebbles with sludge has a different behaviour compared to red mud under fully saturated conditions. After adding 2% shredded paper and 4% saw dust, the tensile yield strength of saturated clay pebbles degrades by 14% and 12%, respectively from its dry strength values. Under soaked conditions, the strength of clay pebbles enhance by 46% and 15% with only sludge and 2% sugar mulch as shown in Fig. 11.

Impacts of moisture in the tensile yield strength degradation of different composite clay pebble types under soaked conditions is important to choose best material mixture for water treatment plant with slow sand filters for using as preliminary filter material. After analysing the tensile yield strength values of composite clay pebbles with different material types and combinations under fully dry and saturated conditions from Fig. 7 to Fig. 11, 25% brick mix-75% red mud with 4% saw dust is best material combination for achieving a higher performance in water treatment process at both construction and operation stages.

Conclusions

Based on the analysis of calculated the tensile yield strength of composite clay balls under dry and saturated condition, following conclusions are drawn:

- Particle image velocimetry (PIV) method is suitable to evaluate both lateral and vertical strain distributions of composite clay pebbles for Poisson's ratio calculation.

- Tensile yield strength of clay pebbles reduces by 54% with burning temperature increment from 800^0C to 1000^0C, however it reaches to its maximum as 1023.33 kN/m^2, when burning temperature is 1100^0C due to change of material characteristics by higher burning temperature. Considering the tensile yield strength, cost, and environment pollution, it is recommended that 800^0C as the best burning temperature for composite clay pebbles.

- Additional of industry wastes such as red mud and sludge can significantly impact on tensile yield strength of hand-made clay pebbles. There is significant the tensile yield strength degradation by the addition of sludge. Composite clay balls with 25% brick mix and 75% red mud proportions provide much stronger material as a filter material

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Notation

The following symbols are used in this paper:

d, D = diameter;

ε_x = lateral strain;

ε_y = vertical strain;

F_s = failure polar force;

L = patch size;

μ = Poisson's ratio;

ρ_{pixel} = precision error and

T_s = tensile yields strength.

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Table 1. Basic material properties

Material	**d10** (mm)	**d30** (mm)	**d60** (mm)	**Cu**	**Cc**	**PL** (%)	**LL** (%)	**size range** (mm)
Brick Mix	0.075	0.200	0.600	8	0.89	16	34	-
Red mud	0.002	0.005	0.022	11	0.46	35	75	-
Sludge	0.110	0.350	1.100	10	1.01	N/A	75	-
Sugar Mulch	-	-	-	-	-	-	-	50-100
Saw dust	-	-	-	-	-	-	-	50-100

Table 2 Poisson's ratio of clay balls (Brick mix) with ball diameter

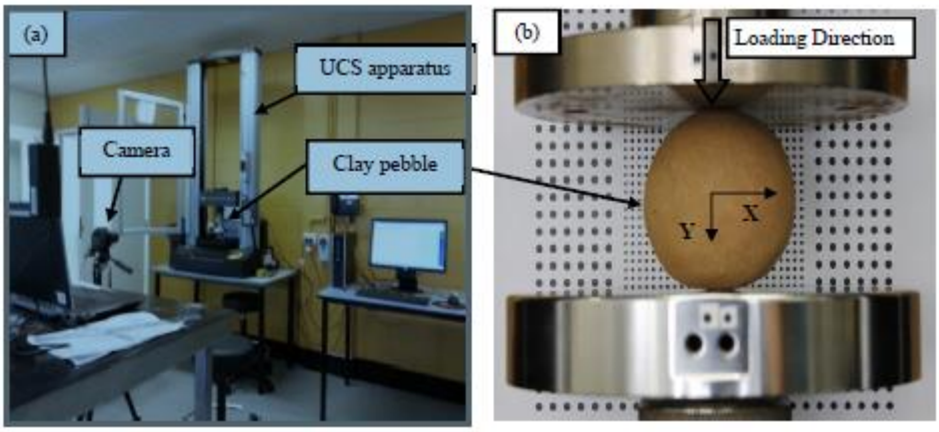
Targeted Diameter (mm)	Achieved Diameter (mm)	Failure polar force, F_s (kN)	Poisson's ratio, ν
20	28 ± 0.69	1.84 ± 0.01	0.21 ± 0.02
30	35 ± 0.46	2.41 ± 0.03	0.23 ± 0.01
40	44 ± 0.95	3.96 ± 0.24	0.25 ± 0.01
50	54 ± 1.36	5.81 ± 0.13	0.23 ± 0.01
60	64 ± 0.38	8.80 ± 0.09	0.22 ± 0.02

Table 3. Poisson’s ratio values of composite clay balls

Brick Mix	Additional Material		Industry Waste			Poisson’s ratio
	Red Mud	Sludge	Shredded Paper	Saw Dust	Sugar Mulch	
(%)	(%)	(%)	(%)	(%)	(%)	
100	0	-	-	-	-	0.23
75	25	-	-	-	-	0.20
50	50	-	-	-	-	0.18
25	75	-	-	-	-	0.16
0	100	-	-	-	-	0.15
100	0	-	2	-	-	0.24
75	25	-	2	-	-	0.21
50	50	-	2	-	-	0.18
25	75	-	2	-	-	0.17
0	100	-	2	-	-	0.16
100	0	-	-	4	-	0.25
75	25	-	-	4	-	0.23
50	50	-	-	4	-	0.20
25	75	-	-	4	-	0.17
0	100	-	-	4	-	0.18
100	0	-	-	-	2	0.24
75	25	-	-	-	2	0.22
50	50	-	-	-	2	0.19
75	-	25	-	-	-	0.16
50	-	50	-	-	-	0.13
75	-	25	2	-	-	0.20
50	-	50	2	-	-	0.15
75	-	25	-	4	-	0.22
50	-	50	-	4	-	0.17
75	-	25	-	-	2	0.19
50	-	50	-	-	2	0.15

List of Figures

Figure 1



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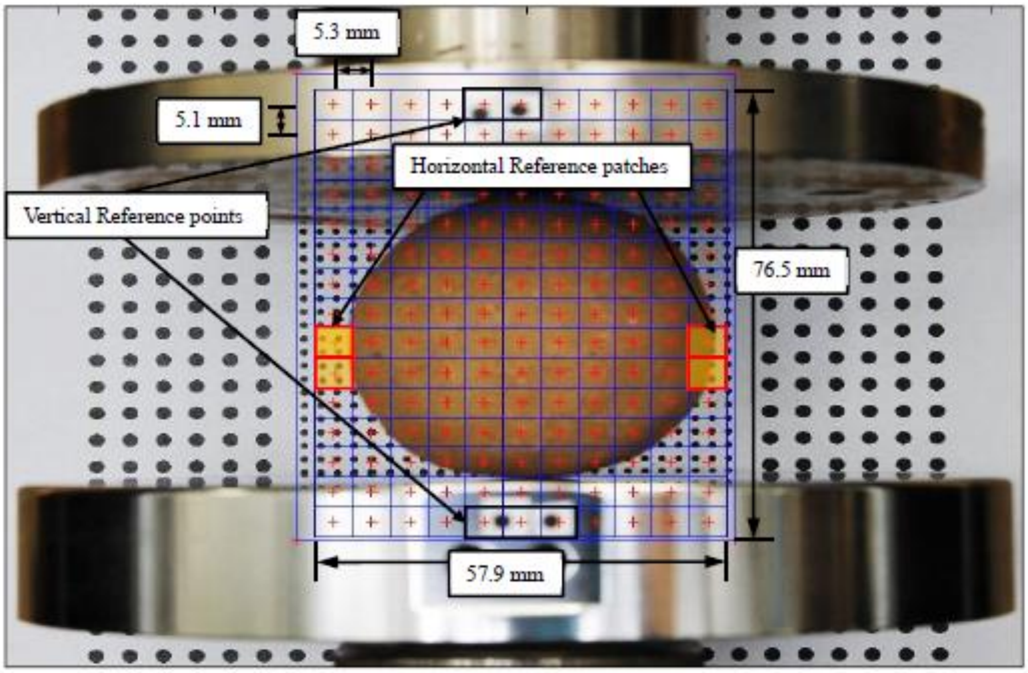


Figure 3

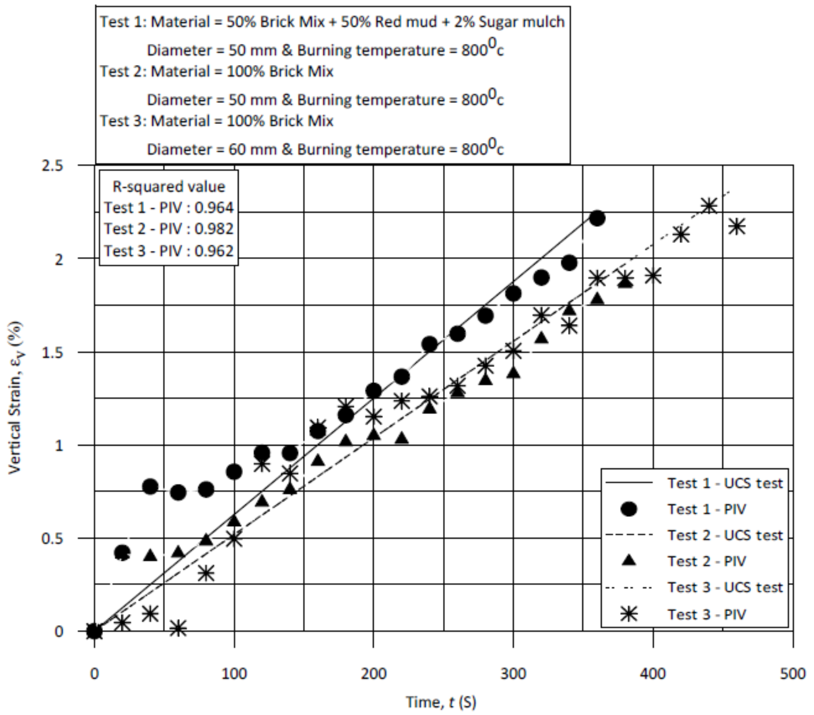


Figure 4

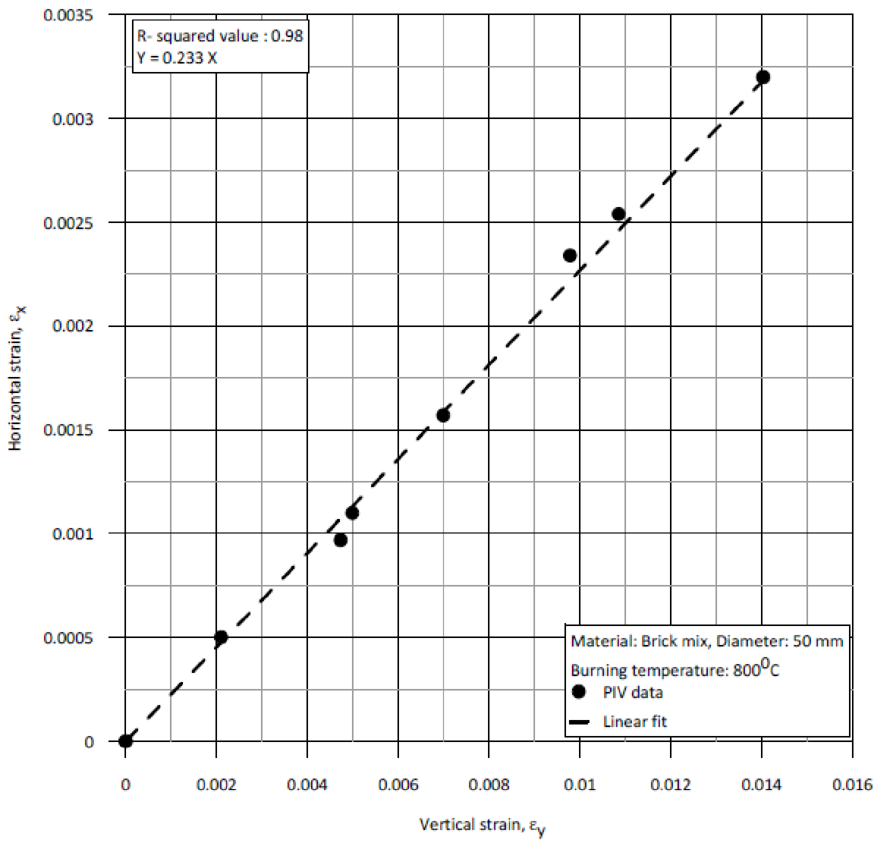


Figure 5

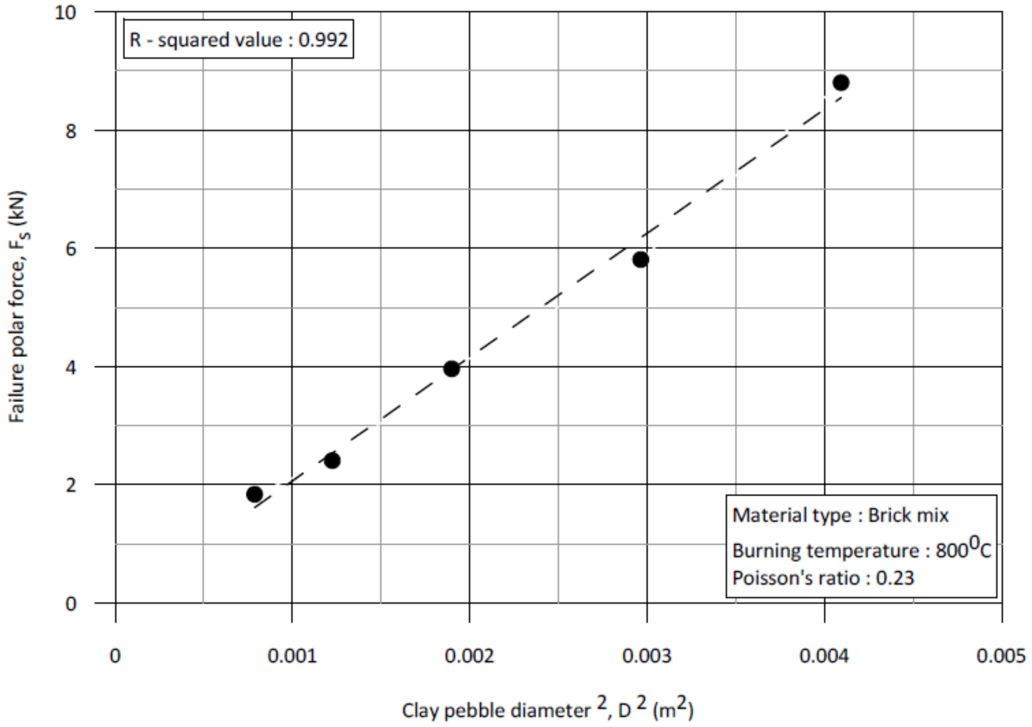


Figure 6

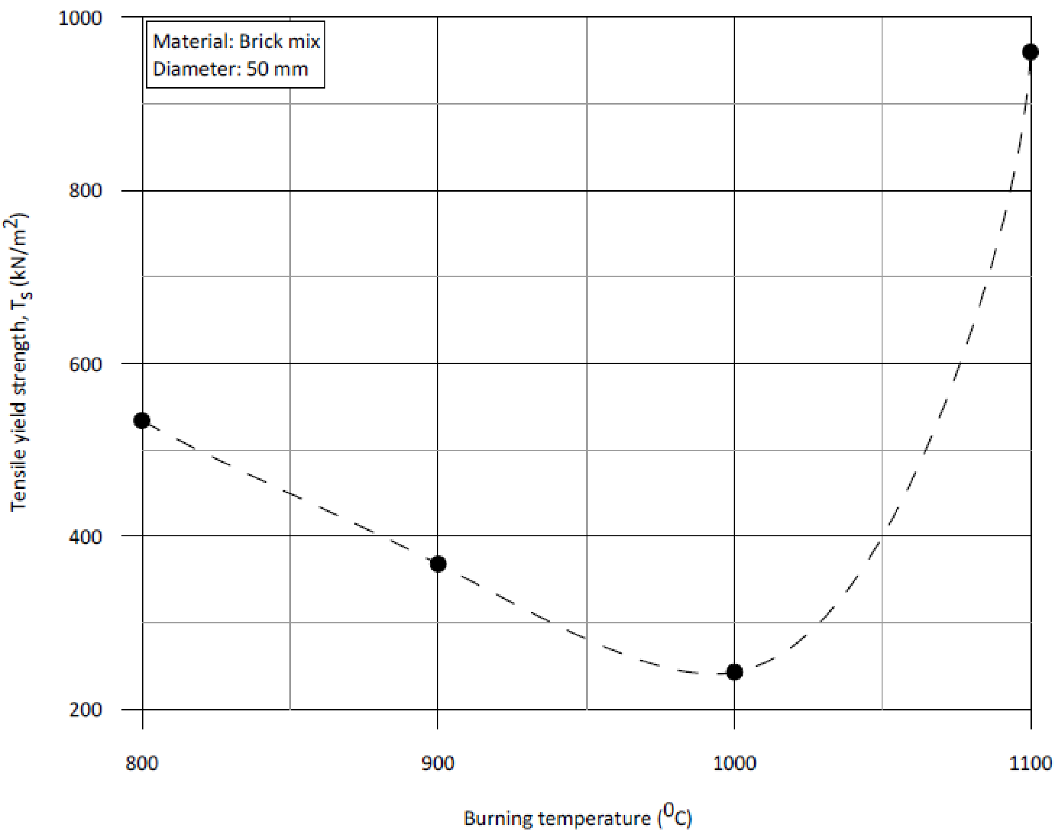


Figure 7

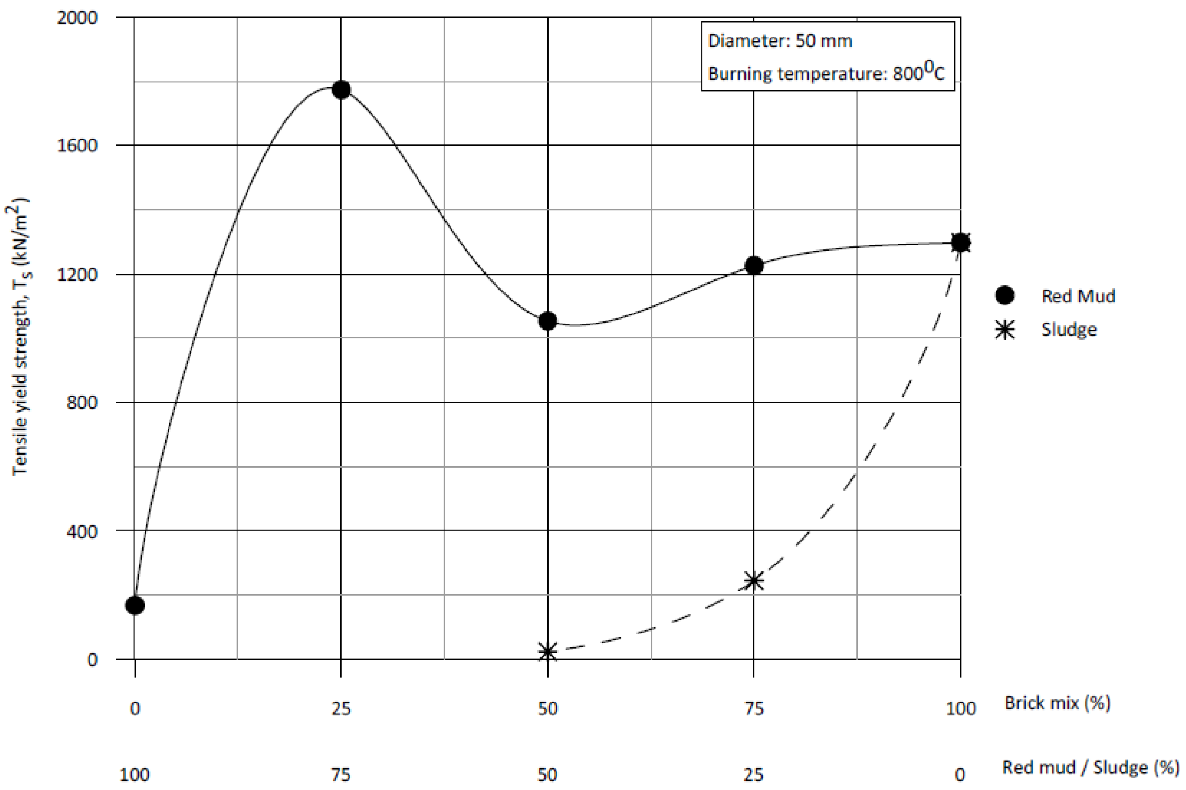


Figure 8

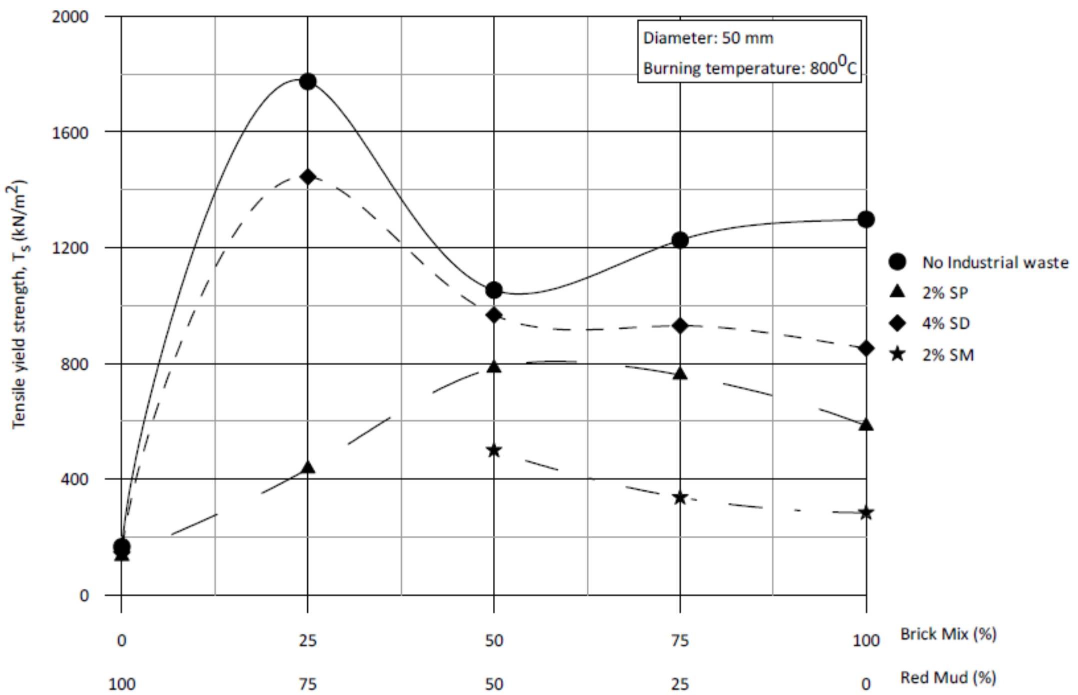


Figure 9

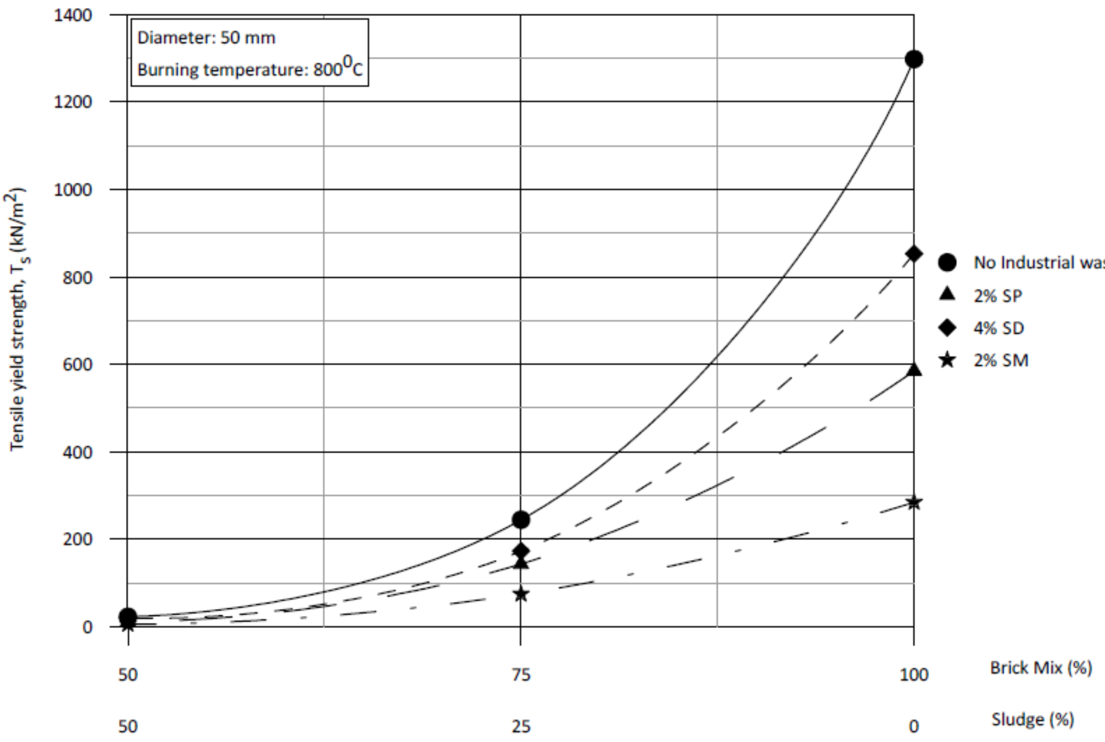


Figure 10

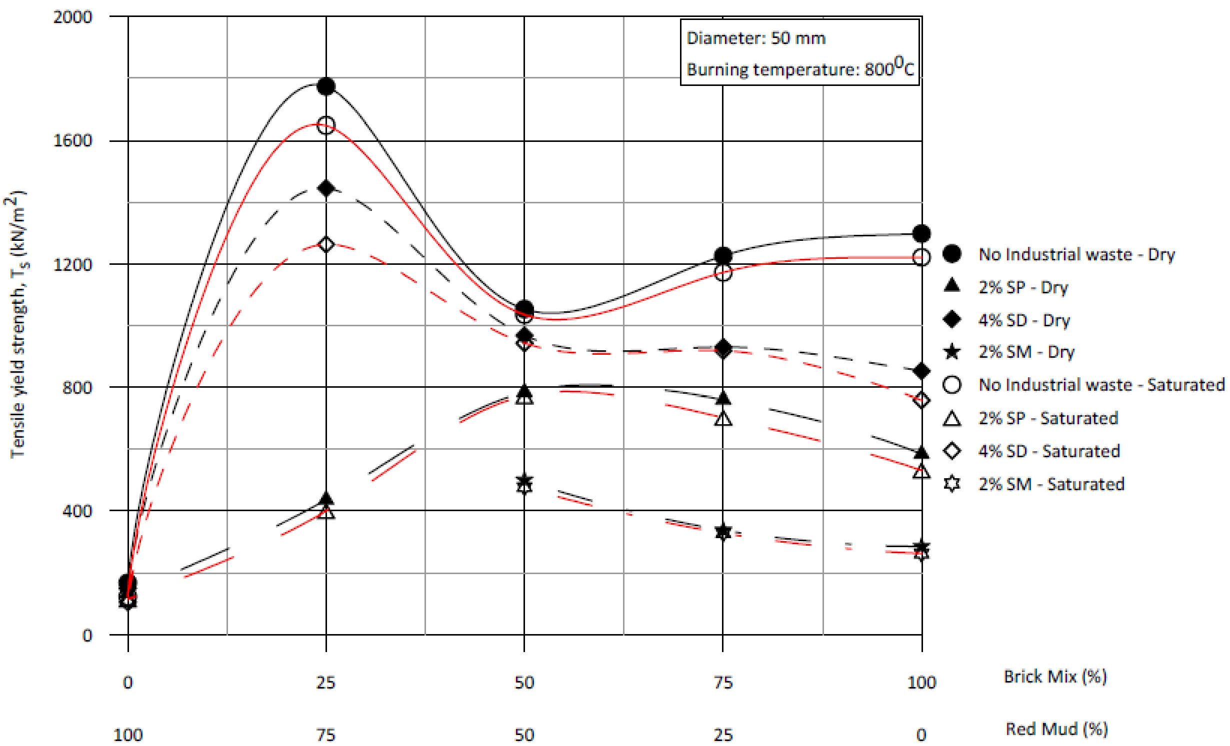
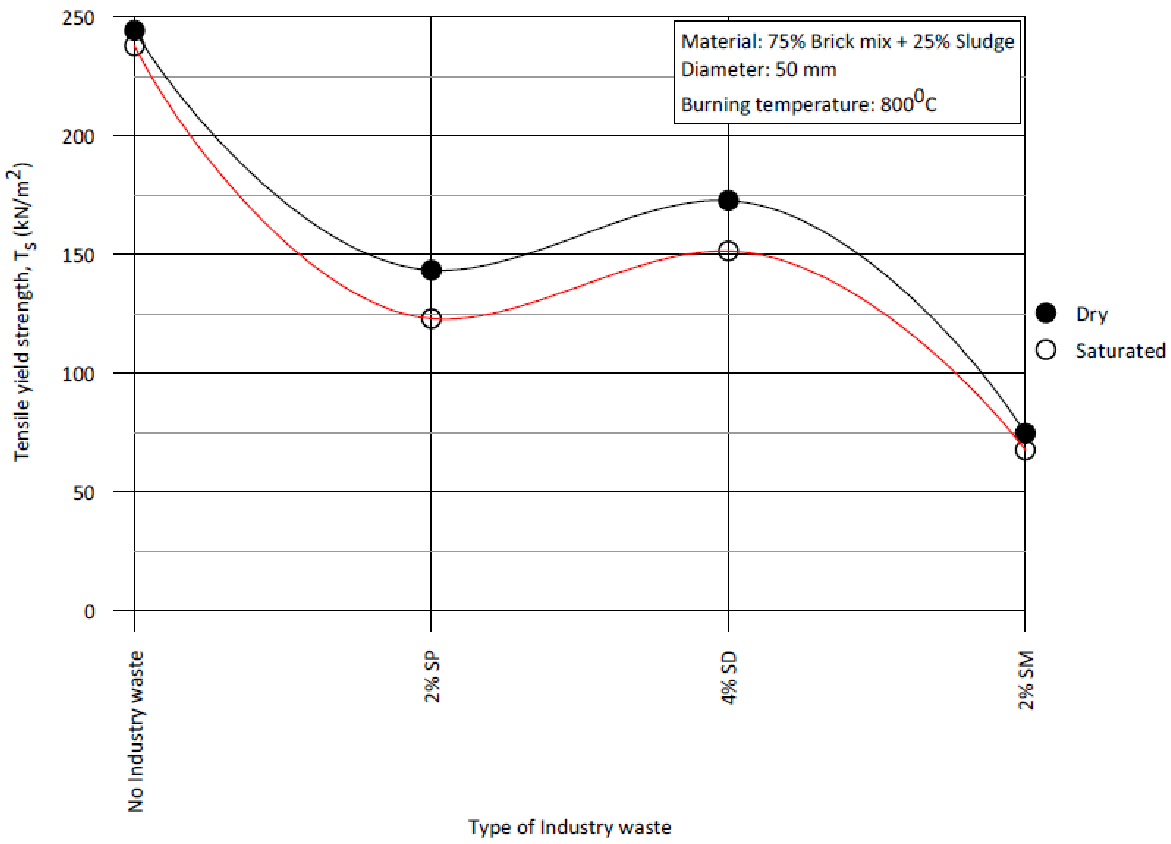


Figure 11


Material: 75% Brick mix + 25% Sludge
Diameter: 50 mm
Burning temperature: 800⁰C
Tensile yield strength, T_S (kN/m^2)
250
200
150
100
50
0
No Industry waste
2% SP
4% SD
2% SM
Type of Industry waste
Dry
Saturated