IEREK PRESS
Academic Research Community
http://www.press.ierek.com
ARChive
ISSN (Print: 2537-0154, online: 2537-0162)
International Journal on:
The Academic Research Community Publication

DOI: 10.21625/archive.v3i3.524

An Economic Assessment for Manufacturing of Insulating Fire-bricks Using Bagasse With 1% Polystyrene

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Abstract

This paper deals with the addition of bagasse with 1% polystyrene (P.S.) as an organic matter to kaolin and grog in a kneader mixer to produce insulating fire-bricks (IFB) with adequate physical and thermal properties.

Clay and grog were mixed in a kneader mixer on a plant scale for twenty minutes to give a paste of ~ 18-20% moisture content. The paste was hand moulded into shapes and dried. The shapes were then fired according to a certain schedule so as to avoid the rapid evolution of gases which causes cracks and destruction of the bricks.

Physical properties such as water absorption, apparent porosity and bulk density were performed according to ASTM. The mechanical properties of these bricks were also determined. Also, the author was able to construct a simple apparatus to measure the thermal conductivity by the comparative method.

It was found that 3 % of bagasse with addition of 1% P.S. is accompanied by an increase in the water absorption and apparent porosity of the fired bricks. It also causes a decrease in cold crushing strength as well as thermal conductivity.

Mathematical relations were developed to relate thermal conductivity to apparent porosity, and thermal conductivity to temperature.

Finally, an economic study was performed for a product of bulk density 1.06 g/cm^3 which showed that the use of 3 % of bagasse with 1% P.S. gives the maximum saving.

Keywords

Insulating fire-bricks- bagasse; polystyrene- thermal conductivity - economic assessment.

1. Introduction

Insulating fire-bricks (IFB) are high porosity refractories of low thermal conductivity. It is suitable for minimizing heat losses in industrial furnaces and that is done by adjusting the ratio, the size of solid particles and pore spaces. In Egypt, the most common raw material used for the production of insulating refractories is fire-clay with a suitable grade to meet the required temperature and other working conditions. Locally, kaolin is mixed with the appropriate amounts of bagasse and foamed polystyrene as a combustible matter. Mixtures of clay, grog and bagasse with foamed polystyrene as a paste are moulded into shapes by hand mouldling and then dried and fired at a temperature of about 1300^{o}C. The combustible matter burns and the products of combustion are expelled from the refractory shapes, which are generally in the form of bricks, and result in a light product having the desired porous structure. A study on the effect of bagasse and foamed polystyrene to the mixture of clays and grog on the fired properties of I FB has been carried out in details to obtain the most economic mix, from the point of view of sum of cost of additive and that of heat loss. Some physical and thermal properties of the produced IFB have been investigated.

2. Experimental techniques:

2.1. Raw materials

2.1.1. Clays

2.1.1.1. Chemical composition of clay

As obtained from XRF, the clay used yielded the following chemical analysis (table 1). The Loss on ignition (LOI) observed (11.35%) is high enough to classify this clay as kaolinitic as this value is fairly close to the hypothetical value of weight loss for kaolinite dehydroxylation (13.9%).

Table 1. Chemical analysis of clay used

Oxide	% by weight
SiO_2	49.24
Al_2O_3	33.41
Fe_2O_3	0.33
CaO	2.68
SO_3	0.54
Na_2O	0.12
K_2O	0.08
TiO_2	1.45
P_2O_5	0.33
SrO	0.21
Cl	0.16
LOI	11.35
TOTAL	99.86

2.1.1.2. Mineralogical composition of clay

Fig. (1) shows the XRD pattern of the clay used. As expected, only lines of kaolinite ($Al_2O_3.2SiO_2.2H_2O$) and quartz (SiO_2). The latter lines are due to the presence of free silica with kaolin. Despite the fact that calcium oxide appeared in XRF, no lines of any calcium compound were obtained, presumably because of the low level of occurrence of these compounds with clay.

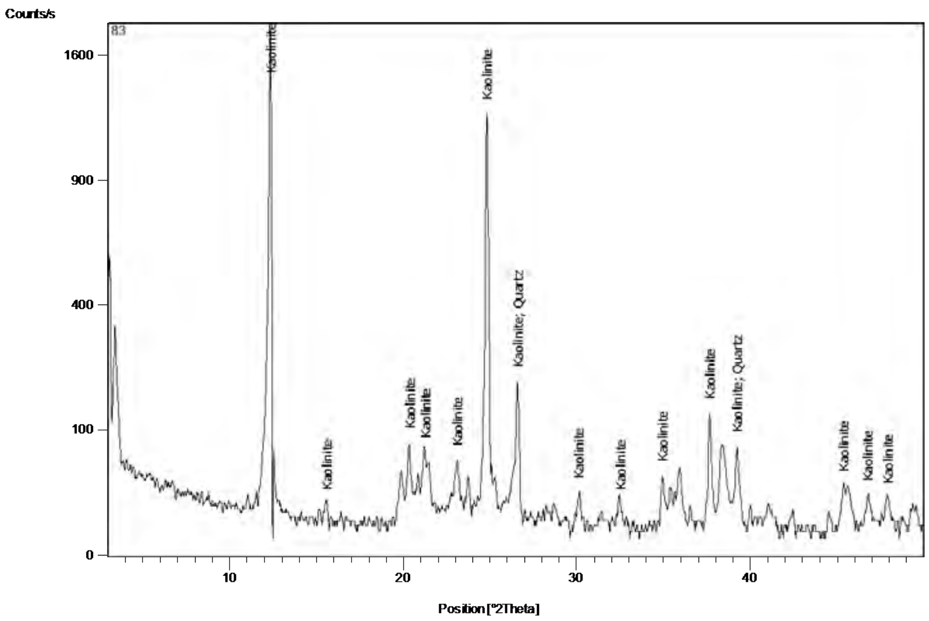

Figure 1. XRD pattern of clay

2.1.1.3. Thermogravimetric analysis of kaolin

The TGA curve for kaolin used in that study is illustrated in figure (2) at heating rate = 10^{o}C.min^{-1} in air.

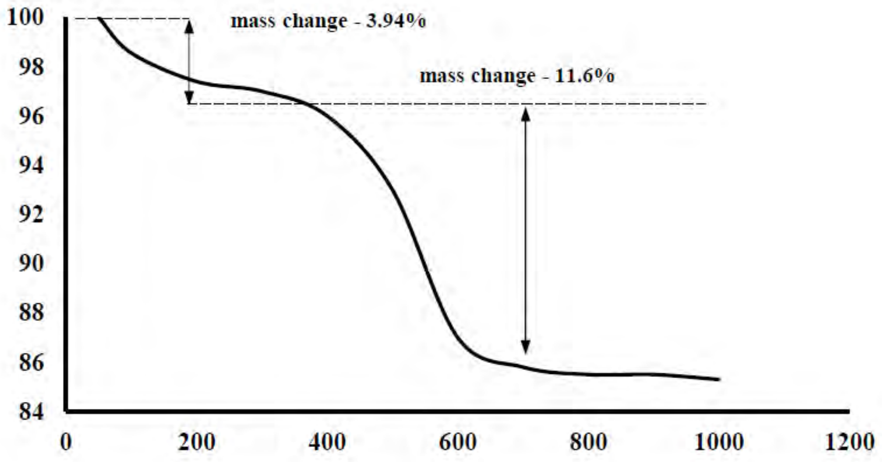

Figure 2. TGA of kaolin

After an initial loss in weight due to loss of physical water, a main peak related to the loss of chemical water and formation of metakaolin takes place. It starts at about 400 ^{o}C and ends at 700^{o}C. The loss in weight associated with that step is 11.6% which is in good agreement with the LOI of a dry sample (11.35%) indicated in table (1).

2.1.1.4. Particle size distribution of clay

The particle size distribution of clay used was determined using a set of standard sieves. The result is illustrated in Figure (3). It indicates that the value of median particle size (D_{50}) is about 0.2 mm.

2.1.2. Grog:

Grog was simply prepared by firing part of the used clay to 1200^{o}C. The produced powder was shown on XRD analysis quartz, mullite ($3Al_2O_3.2SiO_2$) and minor lines of cristobalite. On the other hand, although sintering did take place upon firing, the particle size distribution of grog was relatively close to that of the parent clay with a median particle size (D_{50}) is about 0.33 mm. See (figure 3).

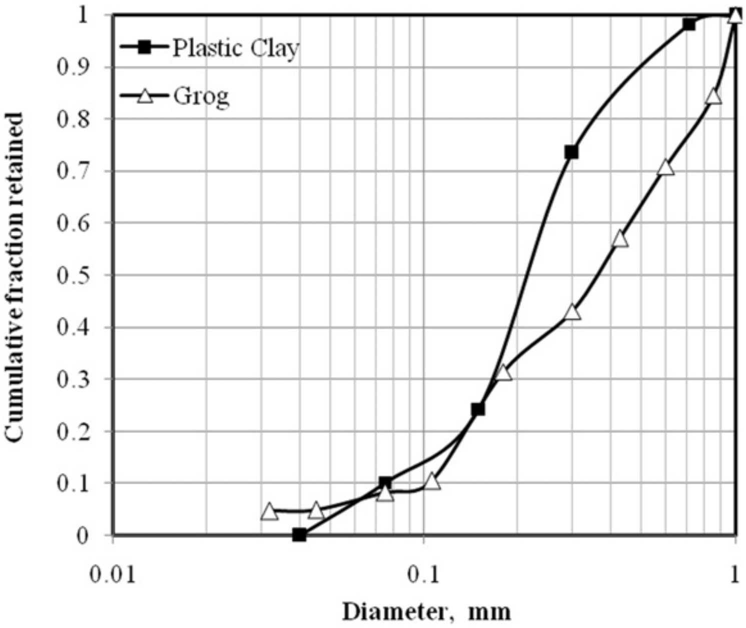

Figure 3. Particle size distribution of clay and grog

2.1.3. Bagasse

Bagasse is the fibrous waste from sugar cane. It wa s supplied from sugar refinery factories, south of Cairo. It was first dried underneath the sun until totally dried. Then, dry bagasse was ground and shredded into small pieces using a size reduction shredder. It was then screened to pass 16 mesh display screen (0.991 mm).

The chemical analysis of bagasse, as obtained from XRF analysis, displayed the components indicated in table 2.

Table 2. Chemical composition of sugarcane bagasse waste

Waste	wt. %
SiO_2	61.59
Al_2O_3	5.92
Fe_2O_3	7.36
MnO	0.1
TiO_2	1.46
CaO	5.00
MgO	1.17
K_2O	6.22
P_2O_5	0.98
SO_3	0.42
LOI	9.05
Total	99.27

2.1.3.1. Properties of bagasse

Bagasse mainly consists of celluloses, hemicelluloses, lignin and ashes with an ash content that may reach 4% (Carvalho, Canilha, Castro, Barbosa, 2009).

The thermal degradation of bagasse has been studied by (Mohomane, Motaung & Revaprasadu, 2017) who found out that it loses 85% of its mass at 380^{o}C after which no more loss was observed.

2.1.3.2. Thermal behavior of a bagasse containing brick

It was interesting before starting investigations concerning the physical, mechanical and thermal properties of the fired bricks to follow up the thermal degradation of the brick components. The corresponding TG performed at a heating rate of 10^{o}C.min^{-1}for a sample containing 1% PS and 3% bagasse is shown in figure (4). In that figure, it appears 5 peaks that can be interpreted as follows:

- Two small peaks that end at 100 and 140 ^{o}C are due to the evolution of physical water.
- Two consecutive peaks ending at about 410 ^{o}C presumably due to the decomposition of bagasse and polystyrene (Xuemei & Hao, 2013).
- A large peak starting at about 500 and ending at 700^{o}C associated with the dehydroxylation of kaolin.

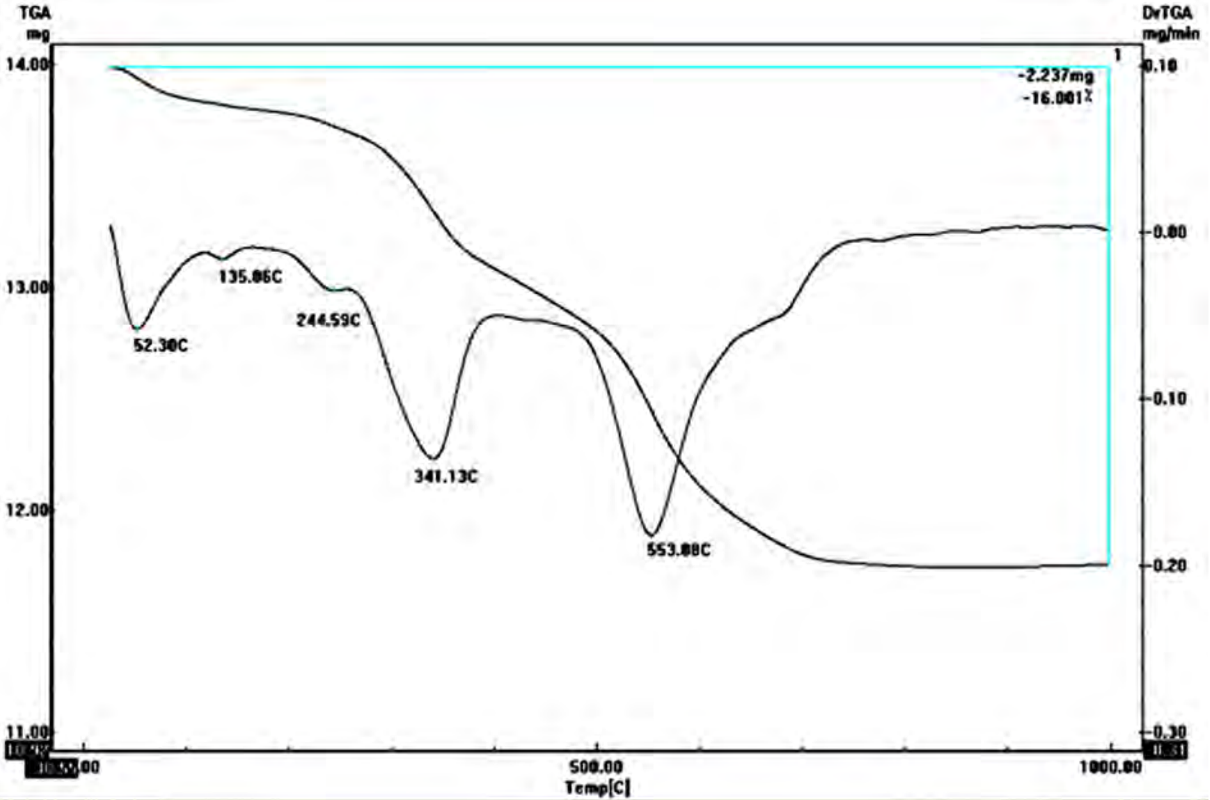

Figure 4. Thermogravimetric analysis of a brick containing 1% PS and 3% bagasse

2.1.4. Water

Water was used with clay to impart the required plasticity. In order to limit any possible efflorescence, the following recommendations concerning the salt contents in water to be used for clay bricks manufacture were reported by (Arafat, Alam, Islam, Das, 2016). As shown in table (3), tap water contains a maximum of 1000 mg.L^{-1} total dissolved solids (TDS), 200 mg.L^{-1} chlorides, 300 mg.L^{-1} sulfates and practically no carbonates, it was safely used in the present work.

Table 3. Recommended chemical limitations for water to be mixed with clay

Chemical species	Max. Conc. Limit
Chlorides as C1	250 mg/l
Sulfates as SO_3	350 mg/l
Alkali carbonates and bicarbonates	500 mg/l
Total dissolved ions, including 1, 2 & 3 above	2,000 mg/l

2.1.5. Polystyrene

Polystyrene beads were purchased from Sigma – Aldrich. They passed 6 mesh screens (3.327 mm) and were retained over 10 mesh screen (1.651 mm). The bulk density was determined experimentally to be 0.035g.cm^{-3}

2.1.5.1. Properties of polystyrene (P.S.)

(Xuemi & Hao, 2013) showed that polystyrene totally decomposes at about 445^{o}C through one large endothermic peak starting at about 360^{o}C. Following 700 ^{o}C, no further weight losses were observed.

2.1.5.2. Thermal analysis of foamed polystyrene

As evidenced from thermal analysis, foamed polystyrene is completely eliminated above 400^{o}C. Oxidation and decomposition start at about 280^{o}C and is completed at about 375^{o}C. A small loss in weight is also observed at 540^{o}C as shown in Fig.(5).This has to be taken care of during firing of samples so as to minimize the risk of brick shuttering due to too rapid evolution of gases (Sokov, 1995; Wendlandt, 1977).

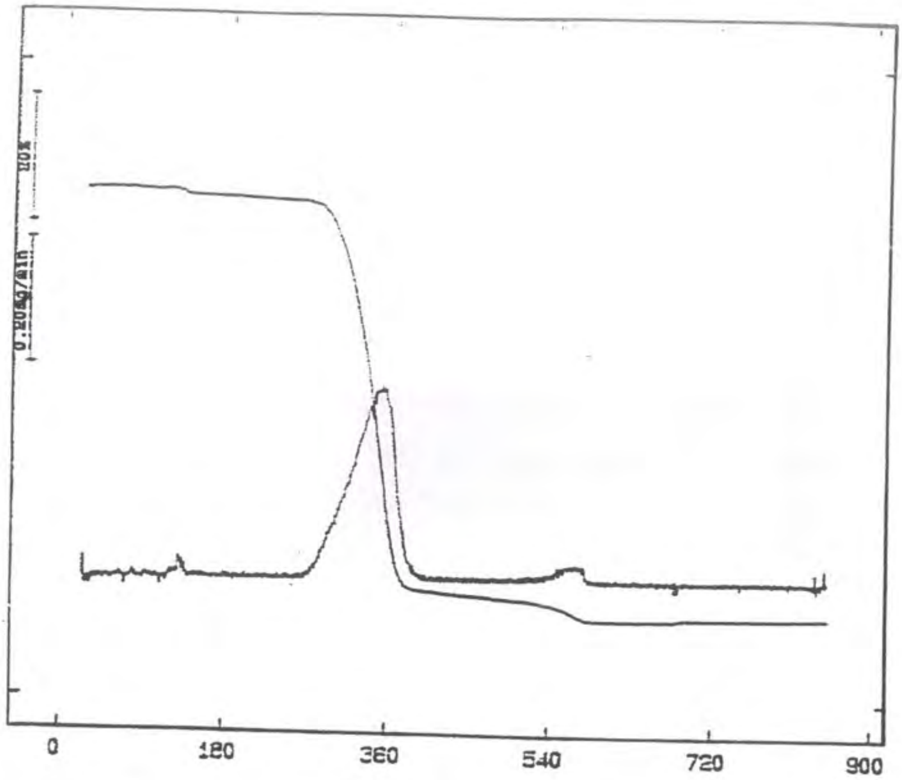

Figure 5. Thermal analysis (TG) for Polystyrene till 800^{o}C

3. Schedule of firing

Firing of specimens containing foamed polystyrene requires great control to avoid cracks in the bricks due to evolution of great amount of gases.

Sokov (5) stated that if the temperature of the green body was raised above 100°C, it may exhibits explosion - like cracks.

The disruption can be pictured as follows :

* above 100^{o}C vapour is formed in the central part of the green body, its over heating leads to the appearance of strong tensile stresses in the mixture.

From 370 to 500^{o}C the loss of mass in the specimens increases markedly. This is clear from the curves describing the loss of mass. The DTA curve in the same temperature interval indicates a great change in the heat content of the tested specimens. This is compatible with the author's finding that above 400^{o}C the polystyrene is pyrolytically decomposed and completely burnt off.

The schedule of heating and firing is as shown in table(4).

Table 4. Schedule of heating and firing in a muffle furnace

Temp.^{o}C	100	140	180	200	225	300	350	450	650
soaking period min.	10	10	10	20	20	20	150	60	20

No gases evolved at the end of heating, so the muffle temperature was adjusted at 1300^{o}C for 5h (De Jonghe, Chu, & Lin, 1989; Monshi & Chahouki, 1993).

4. Construction of a simple apparatus for the measurement of thermal conductivity by the comparative method:

Most apparatuses used for the determination of thermal conductivities at high temperatures use the comparative technique. This consists of using

a specimen of known thermal conductivity to compare with that of the unknown specimen. The method used in that work is that used and detailed by (Tye, 1992).

The apparatus shown in figure (6) consists of a box made of steel 600×600×700 mm^3 in dimensions. The box is internally lined with insulating fire bricks with bulk density of 0.6 gm.cm^{-3} and a thermal conductivity about 0.29 Watt.m^{-1}K^{-1} at 560^{o}C. There is a narrow space between the brick lining and the steel surface of the box filled with glass wool as loose insulation.

Centered inside the box is located a horizontal electric heater of 1.5 kW power. Above the heater a thermocouple (K type) is connected to a temperature controller of maximum working temperature of 1000^{0}C. The sensor of the thermocouple is embedded in a groove on the hot side of the test specimen. The groove depth is 1.5 mm with 100 mm long along the longitudinal section. The reading of the thermocouple is T_1^{o}C which can be adjusted by the temperature controller.

The test sample is laid horizontally above the heater and a thermocouple K type of 2mm diameter is fixed in a groove similar, to that described above on its cold surface. This thermocouple indicates a temperature T_2^{o}C. This is followed by a reference sample RS_1 on the cold face of the sample in which a thermocouple (K type) is fixed and indicates T_3^{o}C.

At steady state, the three readings stabilize and the thermal conductivity of the test sample can be obtained from the following equation using the values of thermal conductivity at various temperatures for the reference sample using the following equations:

$Q = \frac{K_S A\,(T_1 - T_2)}{X_S}$, for test sample (S)

$Q = \frac{K_R A\,(T_2 - T_3)}{X_R}$, for reference sample (R)

Equating the two equations yields:

$$K_S = K_R * \frac{X_S}{X_R} * \frac{(T_2 - T_3)}{(T_1 - T_2)} \quad (1)$$

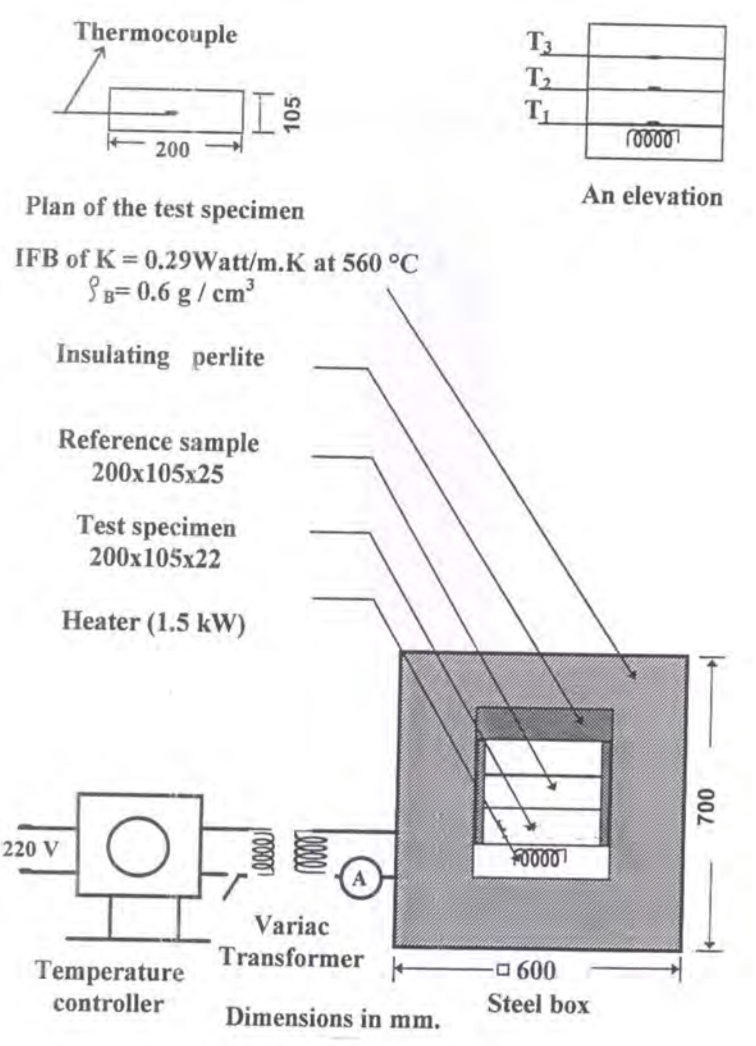

Figure 6. An apparatus to measure thermal conductivity by the comparative method

5. Results

5.1. Physical properties: water absorption, apparent porosity and bulk density, mechanical properties of cold crushing strength and thermal properties

These properties are determined according to ASTM C20-87 (ASTM, 2010).

For each test, the average values obtained with at least five specimens should be reported.

Cold crushing strength is determined according to ASTM C-133 (Wagh, 1993).

5.1.1. Water absorption

Percent water absorption (% W.A) was determined for samples containing varying amounts of bagasse and polystyrene. The results are illustrated in Figure (7).

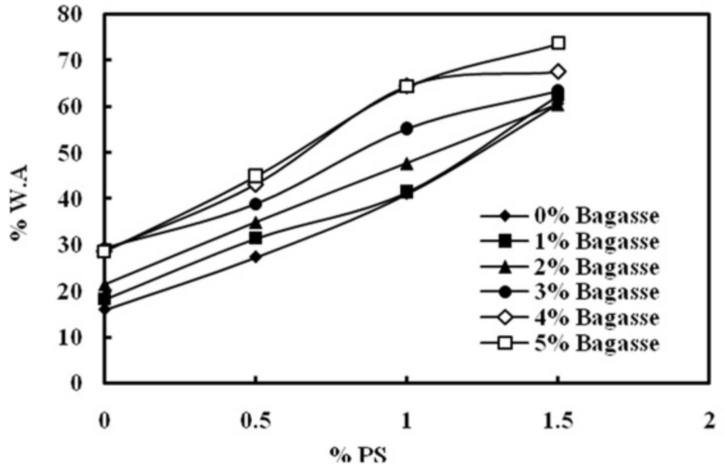

Figure 7. Effect of percent PS andBagasse addition to percent Water Absorption

It was possible to correlate percent water absorption to percent PS and bagasse (B) addition in the following linear expression:

$$\%WA = 14.68 + 27.68\,\%PS + 3.62\,\%B \;\; (R^2 = 0.971) \tag{2}$$

The relative dependence of percent water absorption on both percent PS and bagasse can be viewed in table (5) which assigns correlation coefficients to each variable.

Table 5. Correlation table for WA of Bagasse based bricks

	% PS	% B
% WA	0.915	0.365

It is therefore clear that the effect of PS addition on percent WA is higher than that of bagasse.

5.1.2. Porosity

Figure (8) shows the combined effect of adding PS and Bagasse to the brick. Values of porosity start from 30% for plain bricks containing no addition to reach about 64% at maximum additions of 1.5% PS and 5% Bagasse.

A linear regression equation relating percent porosity to percentage addition of the two pore creators was obtained in the form:

$$\%\,P = 34.42 + 15.06\,\%\,PS + 2.03\,\%\,B \;\; (R^2 = 0.941) \tag{3}$$

As in the case with water absorption, the effect of adding PS on porosity is higher than that of bagasse. This can be seen from the values of correlation coefficients indicating the relative effect of varying both levels of addition on variations in porosity. (Table 6)

Table 6. Correlation table for porosity of Bagasse based bricks

	% PS	% B
% Porosity	0.897	0.370

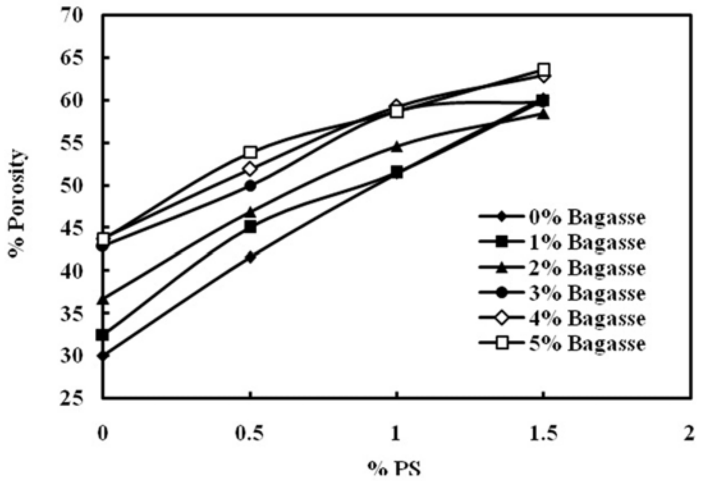

Figure 8. Effect of percent PS and Bagasse addition to percent porosity

A plot of the reciprocal of fractional porosity against the reciprocal of fractional water absorption should yield a straight line of slope $= \frac{\rho_W}{\rho_S}$ and intercept = 1. Actually such a plot when performed resulted in a straight line as shown in Figure (9).

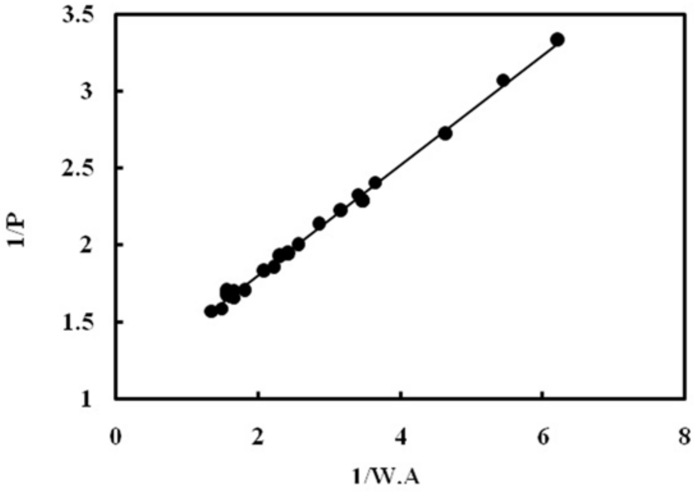

Figure 9. Relation between reciprocals of Porosity and W.A for Bagasse based bricks

The equation of that line takes the form:

$$\frac{1}{P} = \frac{0.36}{W_A} + 1.088 \tag{4}$$

Equation (4) reveals that the intercept is close to unity and that the solid density $= \frac{1}{0.36}$ = 2.77 g.cm^{-3}, a figure fairly close to the experimentally determined value of 2.63

5.1.3. Bulk density

When the bulk density of fired bricks containing PS and bagasse was determined, its dependence on the two types of addition showed an expected decrease upon adding any of the two materials as can be seen in fFigure (10).The figure indicates that adding 1.5% PS with any percentage of bagasse will result in bricks of bulk density$<$1.03 g.cm^{-3}. If 1% PS is added, the minimum percentage of bagasse should be 3%. The correlation table for bulk density was also determined. Table 7 reveals that the effect of adding PS on bulk density is higher than that of bagasse.

Table 7. Correlation table for bulk density of Bagasse based bricks

	% PS	% WS
Density	– 0.919	– 0.334

On the other hand, the regression equation relating bulk density to both percent additions takes the form:

$$\rho B = 1.747 - 0.467\,\%PS - 0.056\,\%B \ (R^2 = 0.956) \tag{5}$$

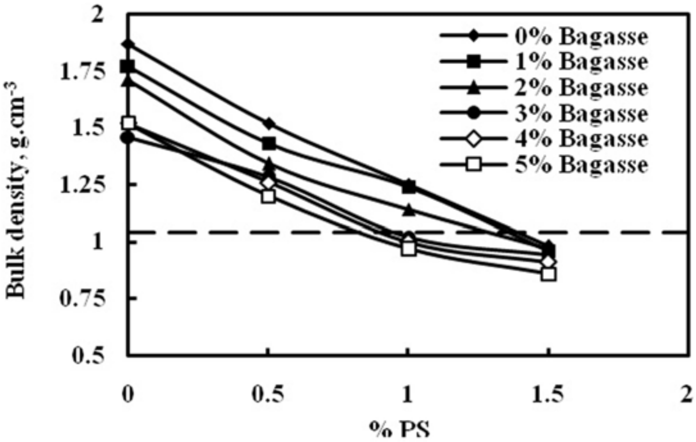

Figure 10. Effect of percent PS and Bagasse addition on bulk density

5.1.4. Cold crushing strength (CCS) of Bagasse based bricks

Figure (11) shows the expected decrease in cold crushing strength following adding any of the two pore formers (PS and Bagasse), although as evidenced by Table (8), the effect of adding PS is more pronounced than that of Bagasse.

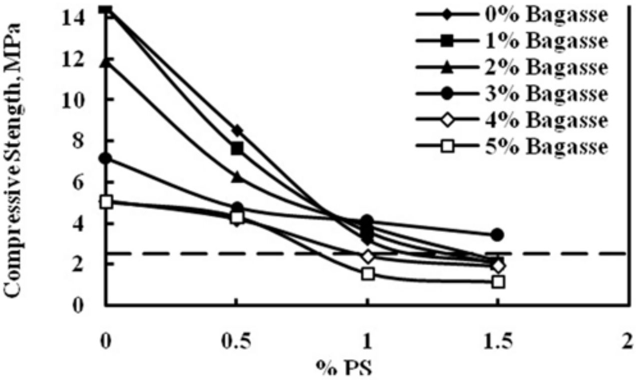

Figure 11. Effect of percent PS and bagasse addition on cold crushing strength

Table 8. Correlation table for CCS of bagasse based bricks

	% PS	% Bagasse
CCS	– 0.770	– 0.419

Here, it was possible, to correlate CCS to porosity by the relation:

$$CCS = 95.54\,e^{-6P} \tag{6}$$

Figure (11) reveals that the maximum percent PS to be added is 1% coupled with at most 3% bagasse in order to exceed the minimum value of 2.5 MPa.

Coupling this condition with that related to bulk density, it seems that the only possible combination fulfilling a maximum bulk of 1.03 g.cm^{-3} together with a minimum CCS of 2.5 MPa, would be 1% PS and 3% bagasse.

5.1.5. Thermal conductivity of Bagasse based bricks

5.1.5.1. Thermal conductivity at 400 ^{o}C

The thermal conductivity of insulating bricks samples was determined at 400^{o}C as function of addition levels of PS and bagasse. As can be seen from figure (12), all compositions tested yielded thermal conductivities less than the maximum allowed value of 0.4 W.K^{-1}.m^{-1}

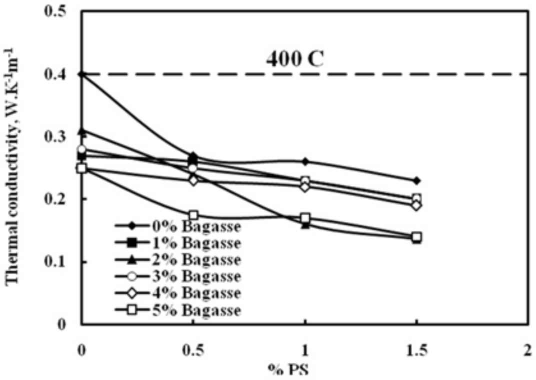

Figure 12. Effect of percent PS and Bagasse addition on thermal conductivity at 400^{o}C

The relation between thermal conductivity and porosity outlined by equation: K=Ko(1-P) was tested in case of bagasse based bricks. The relation illustrated in figure (13) takes the form:

$$K = 0.529 - 0.506\,P \tag{7}$$

As can be noticed, the coefficient of p and the constant term are very close with a mean value of 0.518, which allows writing the previous equation in the approximate form:

$$K = 0.518(1 - P) \tag{8}$$

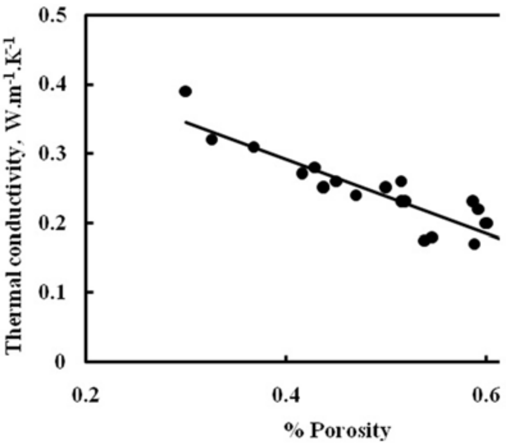

Figure 13. Relation between thermal conductivity (at 400 ^{o}C) and porosity of Bagasse based bricks

5.1.5.2. Thermal conductivity at 600 ^{o}C

The results obtained at 600^{o}C and displayed in figure (14) show an increase in the value of thermal conductivity presumably because of pore radiation. While at 400 ^{o}C, the composition with 1%PS and 3% bagasse, for example, yielded a thermal conductivity of about 0.22 W.K^{-1}.m^{-1}, its value at 600 ^{o}C reached 0.28.

Figure (14) also shows that all investigated compositions produce insulating bodies having a thermal conductivity <0.43 W.K^{-1}.m^{-1} which is the allowable value at 600 ^{o}C for C–30 insulating fire bricks.

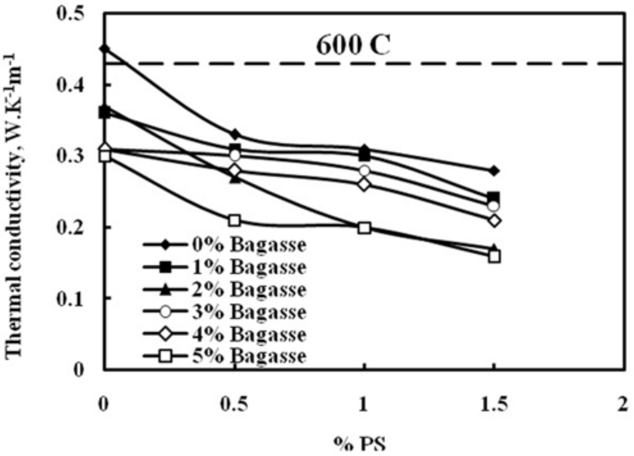

Figure 14. Effect of percent PS and Bagasse addition on thermal conductivity at 600^{o}C

5.1.5.3. Thermal conductivity at 800 ^{o}C

Similarly, thermal conductivities of prepared bricks were determined at 800 ^{o}C. The results displayed in figure (15) show that, with few exceptions, most of the mixtures investigated resulted in thermal conductivities less than 0.44 W.K^{-1}.m^{-1}, which represents the maximum allowable value at 800^{o}C.

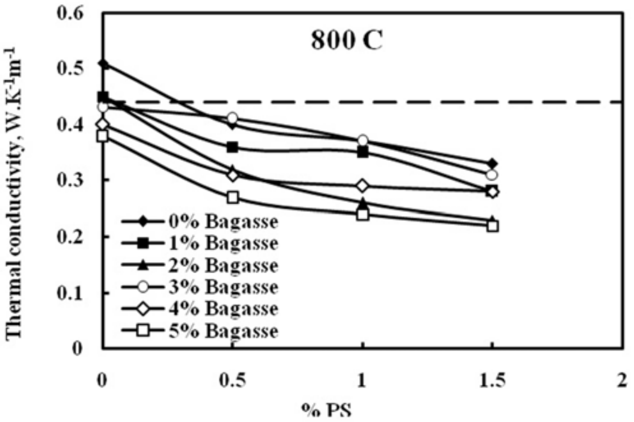

Figure 15. Effect of percent PS and Bagasse addition on thermal conductivity at 800^{o}C

6. Simple economic assessment

To summarize the previous findings, it must be borne in mind that the three main properties that have to be fulfilled for the chosen type of insulating fire bricks are the bulk density, cold crushing strength and thermal conductivity. The following table reviews the standard properties of C–30 insulating bricks and the corresponding obtained values for bricks prepared with 1% PS only mixed with 3% of bagasse gives bricks fulfilling the bulk density (1.06 g.cm^{-3}) as shown in table 9.

Table 9. Properties of chosen composition of insulating refractory brick

Property	Bulk density g.cm^{-3}	CCS MPa	KW.m^{-1}K^{-1}(800^{o}C)
Brick with 1% PS + 3% Bagasse	1.06	4.08	0.42
Brick with 1% PS	1.24	3.1	0.42
Standards	Max 1.03	Min 2.5	Max 0.44

K values were used to establish a linear relation of the form:

$$K = a + bT \tag{9}$$

The values of thermal conductivity at a brick mean temperature of 1000°C, for bagasse and 1% P.S were estimated from equations (9) . With this mean temperature, a temperature gradient of 2.5°C/ mm and a brick thickness of 23 cm, the corresponding maximum, brick face, temperature is estimated to be 1288°C (2350 ^{o}F). Although this value exceeds the value of 2000 ^{o}F, it is still well below the value of 2800 °F and there is no indication, that the temperature gradient is not linear for bcks used to stand temperatures up to 2350 °F. It is reasonable to believe that any departure from linearity, at this temperature, is only slight, and that equations of the form of equation (9) are still valid.

$b = \frac{k_{800^0c} - k_{500^0c}}{800-500}$ & $a = \frac{800\,k_{500^0c} - 500\,k_{800^0c}}{800-500}$

We consider now a temperature gradient of 2.5°C/mm (which is close to industrial conditions using the tested IFB) through an existing tunnel kiln, at Helwan plant for refractories, when lined with the tested IFB with thickness 23 cm. The longitudinal section of the firing zone to be lined in the tunnel kiln consists of two walls 50 m long, of height 3.50 m, and with 23 cm thick lining (this requires 46823 bricks of dimensions 23xll.5x6.5 cm^3, of total weight 88.55 Ton), corresponding to a bulk density of 1.06 g/cm^3.

The life time of such bricks is about 1 year, so that basic calculations on one year seams a reasonable choice.

From actual data taken at the aforementioned factory site, it was found that the manufacturing cost of P. S. free fired bricks, having the same % age of alumina and the same dimensions as the I FB under study, is about 12 LE/brick. To this, should be added the cost of P.S. used which will depend on the percent added.

P.S. of different size fractions costs 35.000 LE/Ton .Since the average weight of a brick is about 1.82 kg for ((23 x 11.5 x 6.5 cm^3) x 1.06)/1000, hence an addition of, say, X% of P.S. would cost:

$1.82\,\frac{X}{100} \cdot \frac{35000}{1000} = 0.637X\;LE/brick$

So that the cost of a brick :

= 12 + 0.637 X LE/brick

Considering a net benefit of 30% for such bricks made by hand molding, the selling price is:

=15.6 + 0.828 X LE/brick

For our case of using 1% P.S and 3% bagasse which is priceless waste , the bricks should be sold at a price of 16.5 L.E/brick.

The rate or heat loss per brick can be calculated as follows:

$Q = K.A\frac{\triangle T}{\triangle X}$

Q = K(0.115XO.065)2.5x10^3 = 18.69 K Watt / brick

Where:

K = the mean thermal conductivity measured at (T$_1$ + T$_2$)/2

$\triangle T = T1 \; - \; T2$

ΔX = thickness of insulating fire-brick.

Consider now the cost of heat loss per year using 3% bagasse and 1% P.S using the conservative figure of 1.5L.E.

for KW.H, we get:

Cost of heat loss per year per brick

$$= 18.69\, x\, 24\, x\, 30\, x\, 12\, x\, 1.5x\, 10^{-3}\, K \;=\; 242.2\, K\, L.E./brick \tag{10}$$

Hence, the total annual cost of purchasing one brick + heat loss

= 16.5 + 242.2 K, for 3% bagasse and 1% P.S

The total annual cost for the whole wall is, hence :

46823 x (16.5+ 242.2 K) LE/year

At 500°C, for instance, K = 0.389

Hence: total cost = 5,184,045.9 LE.

A similar calculation was performed at temperature of 800°C gives 5,535,602.E. The results are presented in table 10.

Table 10. Total annual cost associated with a brick wall lined with IFB 88.55 Ton (ρ_B = 1.06 g/cm^3) in LE

average brick temperature	fraction	cost of bricks	cost of heat loss	total
500°C	3%B. +1%P.S	772,579	5,184,045.9 LE	5,956,624
800°C	3%B. +1%P.S	772,579	5,535,602.E	6,308,181

We can therefore conclude that it is more profitable for the customer to buy type 1.06 g/cm^3 insulating bricks despite its higher purchasing cost, since, in the long run, the total expenditure will be lower. It will therefore be recommended, for future production, that only such types of bricks be produced, and that the customer must be made aware of the reasons for the change in the company policy.

Total selling price / year = 46823 x 16.5 =772,579 LE

We assume now that the value of the conductivity of such bricks (at 800°C) is equal to the value reported in table (10).

This gives an annual cost of heat loss equal to 5,535,602.E LE.

The total cost is, therefore, 772,579 LE +5,535,602=6,308,181LE.

If the customer chooses to buy this type, as recommended, then, as is clear from Table 10, this will cost 772,579 LE/year, meaning a saving of 5,535,602 L.E year, despite the lower initial purchase cost of the type brick (16.5 LE/brick).

7. Conclusion

The economic study was performed for a product of bulk density 1.06 g/cm^3 showed that the use of bagasse 3% with 1% P.S. gives adequate saving.

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