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Effect of firing temperature on physico-mechanical properties of contemporary clay brick productions in Lalitpur, Nepal

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Abstract

Effect of firing temperature on some physico-mechanical properties of ten brick samples, those were composed by feldspars, quartz, alumina-rich spinel, primary mullite and hematite phases, was investigated in accordance with ASTM standards. The brick samples fired between 700° to 1100° C showed 11-23 % water adsorptivity (WA), 19-37 % apparent porosity (AP) and 1.50-1.65 g/cm³ bulk density (BD) indicate good physical properties. The maximum compressive strength (CS) of the fired-bricks at 950° to 1000° C was found to be between 15.6 and 17.1 MPa. At 700°-1000° C firing temperatures, the CS of these bricks is found to be increased exponentially with decreasing of both WA and AP, however it is found to be increased with increasing the BD. Consequently, it can be said that there is good correlation between mechanical and physical properties of the fired-brick samples up to the firing temperature of 1000° C.

Introduction

The clay brick is perhaps one of the man-made durable structural materials so far and their use has been increased since Mesopotamian, Egyptian and Roman periods (Fernandes *et al.*, 2010). In modern age, its widespread use is mainly due to the availability of clay minerals in most countries of the world. The best quality of bricks depends on the types of clay raw materials used and the firing temperature during their production, because both of these parameters affect the quality and durability of bricks (Mostaghelchi *et al*., 2013; Johari *et al.*, 2010; Rasmussen *et al.*, 2012; Dunham *et al.*, 2001; Dondi *et al.*, 1999). It is said that the durability (i. e., mechanical strength) of the clay brick samples depends mainly on their mineralogical composition and physical properties like water absorption capacity, porosity, density and so on (Bordia and Camacho-Montes, 2012). The mineralogical, physical and mechanical properties of the fired bricks are generally interrelated to each others. It was reported that the firing temperature was found to be one of the key factors to modulate the physico-mechanical properties of different types of ceramic

bodies like bricks (Ajala *et al.*, 2017a, 2017b; Velraj *et al.*, 2009; Karaman *et al.*, 2006), but not the firing rate on kaolinite-based ceramics (Njoya *et al.*, 2017). The physical properties of clay brick samples and their mechanical strength were investigated at different firing temperatures and the samples fired at 1100 °C showed the best mechanical properties (Johari *et al.*, 2010; Aramide, 2015; Dodoo-Arhin *et al.*, 2013; Martin-Marquez *et al.*, 2010; Ghorbel *et al.*, 2008; Yongue-Fouateu *et al*., 2016).

On the other hand, the porosity and water absorbtivity of the fired clay bodies were reported to decrease with increasing their firing temperature, while the density and Young's modulus of elasticity of the clay bodies were increased with increasing the temperature (Aramide, 2015; Yongue-Fouateu *et al*., 2016). The porosity influences quite dramatically the mechanical strength of ceramic bodies like bricks; for example, it is not uncommon that 10 % volume porosity generally helps to decrease the flexural strength by 50 % of the measured value for the nonporous materials (Callister, 2007; Coble and Kingery, 1956). The flexural strength (σ_F)

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generally decreases exponentially with volume fraction porosity (P) (Callister, 2007) as given equation (1) below, where σ_0 and n are experimental constants.

Flexural Strength $(\sigma_F) = \sigma_0 \times \exp(-nP)$ (1)

The durability assessment of different types of clay bricks is mainly based on their technical physico-sintering and mechanical properties. However, such technical properties of the archaeological clay brick samples of Kathmandu valley (Ghale *et al.*, 2019) and ceramic tiles (Budathoki *et al.*, 2018a, 2018b) were studied by few research groups in Nepal. Considering these facts, the present research work was focused to carry out an investigation of the firing temperature effect on the physical properties of WA, AP, BD and one mechanical property, i.e., CS of total twenty eight fired clay brick samples using ASTM standards (ASTM C20-00, 2015; ASTM C1424-15, 2015) to find out their physico-mechanical properties.

Materials and methods

Firing of brick samples

Twenty five pieces of sun-dried clay brick sample specimens and three pieces of fired clay brick sample from Shiddi Vinaayak Chimney Vattaa Factory- Lalitpur of Kathmandu valley, Nepal were used to accomplish present research work. Twenty four, among these twenty five pieces of the sun-dried clay brick samples, were fired at 700º, 750º, 800º, 850º, 900º, 950º, 1000º and 1100º C with three pieces (i.e.,

specimen-1, specimen-2 and specimen-3) for each firing temperatures using muffle furnace maintaining two hours soaking period and remaining one piece of the sun-dried brick sample was used to estimate their physico-sintering and mechanical properties for comparison. The fired brick sample produced by factory itself is named as NB-FPr. The details about these clay brick samples used in the study are summarized in Table I.

Estimation of physical properties

It is meaningful for mentioning here that the mineralogy of these ten brick samples was previously reported to be consisted mainly of quartz, feldspars, spinel, primary mullite and hematite including muscovite type of mica minerals (Bohara *et al.*, 2018). In this study, three physical properties of the fired- brick samples were estimated using following equations (2), (3) and (4) in accordance with ASTM C20-00 standards (ASTM C20-00, 2015), where W_D is dry weight (g), W_S is saturated weight (g) and V_b is volume of outer sides (cm³) of the brick specimens.

$$\text{Water absorption (\%)} = \frac{W_S - W_D}{W_D} \times 100 \quad (2)$$

$$\text{Apparent porosity (\%)} = \frac{W_S - W_D}{V_b} \times 100 \quad (3)$$

$$\text{Bulk density (g/cm}^3) = \frac{W_D}{V_b} \quad (4)$$

Table I. Details about the clay brick samples used in this study

Name of brick samples	Firing temperature (°C)	Remarks
NB-0	-	Sun-dried brick
NB-700	700	Fired at muffle furnace
NB-750	750	Fired at muffle furnace
NB-800	800	Fired at muffle furnace
NB-850	850	Fired at muffle furnace
NB-900	900	Fired at muffle furnace
NB-950	950	Fired at muffle furnace
NB-1000	1000	Fired at muffle furnace
NB-1100	1100	Fired at muffle furnace
NB-FPr	Unknown	Fired at factory

Estimation of compressive strength

The compressive strength (CS) of the clay bricks was estimated using the RAM DIA 222-2 mm with maximum load of 2000 KN compression testing (CT) machine available at the Central Material Testing Laboratory, Department of Civil Engineering of Pulchowk Engineering Campus, Tribhuvan University, Lalitpur using equation (5) in accordance with ASTM C1424-15 standards (ASTM C1424-15, 2015) as given below.

$$\text{Compressive strength (N/mm}^2)$$
$$= \frac{\text{Maximum load at failure (N)}}{\text{Average area of bed face (mm}^2)} \quad (5)$$

For the CT test, the clay bricks were immersed in water at room temperature for 24 hours and then the samples were removed from the water. The surplus water of the sample surface was drained out using smooth moisten cloth at room temperature. The unevenness observed also removed for the smooth parallel faces. The capping was subjected to the CT machine to estimate the compressive strength of the clay bricks.

Results and discussion

Firing temperature effect on physical properties

Different physico-mechanical properties of the fired brick bodies are reported to be mostly influenced by their mineralogical composition and firing temperature (Karhu *et al.*, 2019; Johari *et al.*, 2010; Karaman *et al.*, 2006; Braganca & Bergmann, 2003). For example, fluxing oxides contained in brick clay materials play one of the very important roles for the improvement of physico-mechanical properties of the fired-brick bodies (Sokolar *et al.*, 2017, Sokolar & Vodova 2015; Alcantara *et al.*, 2008). Some basic physico-sintering properties of water adsorptivity, bulk density and apparent porosity and some mechanical properties of flexural and compressive strength act as the quality control parameters of the clay products like tiles (Budhathoki *et al.*, 2018a).

To assess the quality of the clay bricks production in Kathmandu valley, the firing temperature effect on their some important physico-sintering properties is mostly considered and different physico-sintering properties should be correlated with their mechanical strength of compressive strength. It was reported that water absorption capacity became one of the important criteria for showing high quality and good strength of clay bodies like tiles (Budhathoki *et al.*, 2018a). Consequently, it can be assumed that a lower amount

of water retention capacity is always in demand for good quality brick production.

Change in water absorption capacity of brick sample with firing temperature

Figure 1 shows the effect of firing temperature on the water absorption capacity of all test specimens and their average
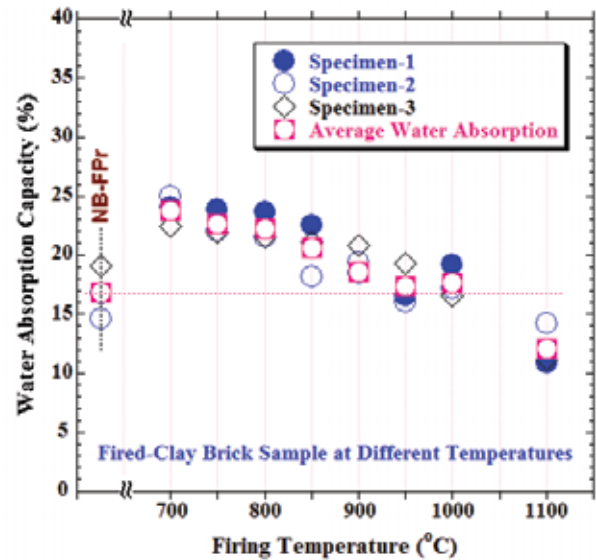

Fig. 1. Changes in the water absorption capacity of the clay brick samples as a function of firing temperature

values of the fired clay brick samples. The fired clay brick samples used in this study showed 11-25 % water absorption capacity. A slight decrease in the water adsorptivity with increasing the firing temperature of the clay brick samples fired up to 1000° C is clearly observed (Fig. 1). The water absorption capacity of the brick sample fired at 700° C is slightly higher than that of the fired brick sample at about 1000° C in laboratory and produced by the brick factory itself, i.e., NB-FPr sample. It is meaningful for mentioning here the facts that the brick samples fired between 900° and 1000° C have almost same amounts of water absorption capacity as compared with the brick sample produced by the brick factory using their chimney. Consequently, it can be said that the brick samples produced by the brick factories of Kathmandu might be fired at around 900° to 1000° C.

Change in bulk density of brick sample with firing temperature

Results of the estimated bulk density of total twenty eight fired brick specimens at different temperatures are shown in Fig. 2 which cleared that the twenty four fired brick

specimens at eight different temperatures between 700° to 1100° C show 1.54-1.77 g/cm³ of bulk density; while the brick sample NB-FPr (produced by brick factory) show about 1.71 g/cm³ only. It is meaningful to mention here that the densification behavior was reported as function of firing temperature of the ceramic bodies (Budhathoki *et al.*, 2018a) and hence the densification of the presently analyzed brick samples attained the maximum value at temperatures between 900° and 1100° C and hence fired-brick samples at this temperature range show maximum bulk density as depicted in Fig. 2.
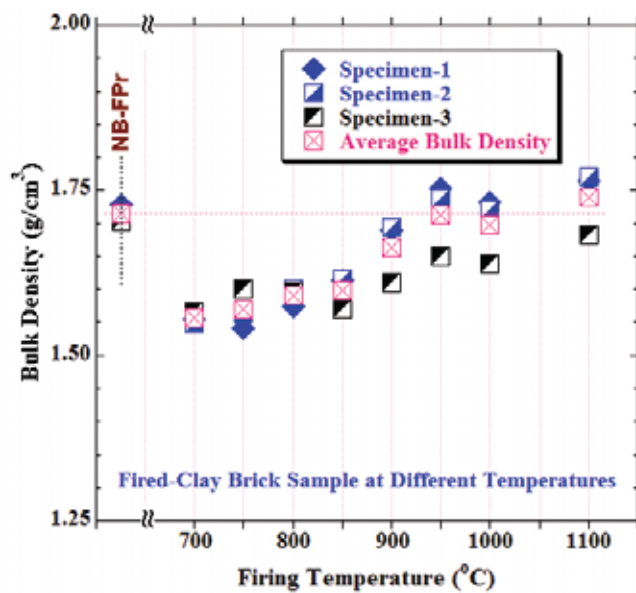

Fig. 2. Changes in the bulk density of the clay brick sample specimens as a function of firing temperature

Change in apparent porosity of brick sample with firing temperature

Similarly, the effect of firing temperature on the apparent porosity of all specimens and their average values of the fired clay brick samples is depicted in Fig. 3. All the fired clay brick samples showed the apparent porosity between 16-39 % and a slight decrease in the apparent porosity with increasing the firing temperature of the clay brick samples fired up to 1000° C is clearly observed (Fig. 3). However, the apparent porosity at 1100° C is significantly lower value than of the brick sample specimens fired at 1000° C. It is meaningful for mentioning that the brick sample NB-FPr (produced by brick factory) shows the average apparent porosity about 27 % only.

Figure 4 shows a clear co-relation between the water absorptivity, apparent porosity and bulk density of all the fired brick sample specimens used in the present work as a
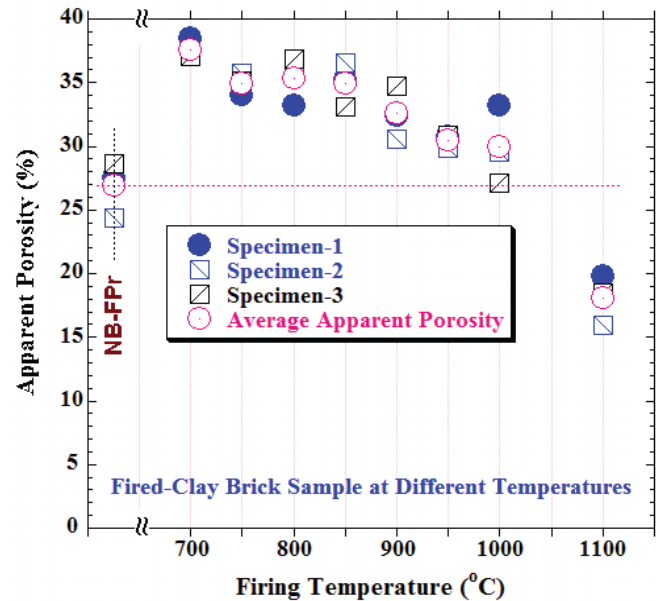

Fig. 3. Changes in the apparent porosity of the fired brick sample specimens as a function of firing temperature
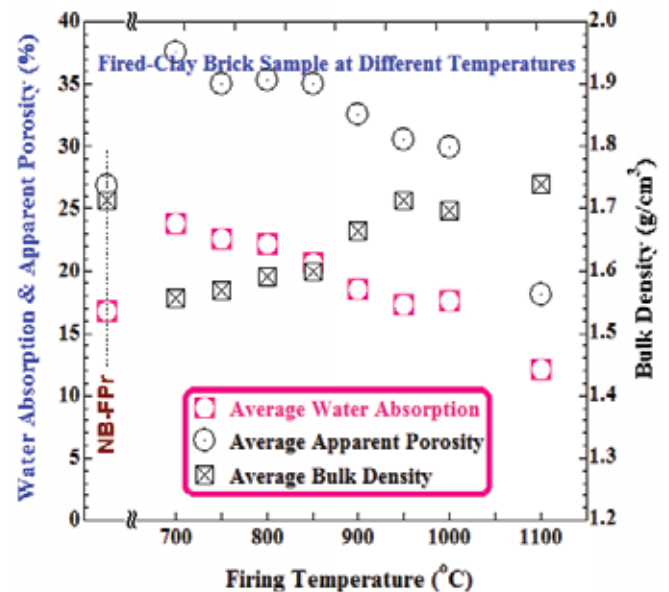

Fig. 4. Firing temperature effect on the water absorption capacity, apparent porosity and bulk density of the fired clay brick samples

function of firing temperature. In most cases, it is observed that the fired ceramic bodies like tiles or bricks have high bulk density as well as the mechanical strength with low water absorption capacity as well as apparent porosity. From the present results, it is observed that there is a good correlation between the water absorptivity, apparent porosity, bulk density and firing temperature for all analyzed clay bricks. The water absorptivity and apparent porosity of the brick specimens decrease and the bulk density increases with increase of temperature as shown in Fig. 4. These results are mostly supported by the facts that the low density values observed for the brick structures at lower temperature are directly related to their high values of water absorptivity or apparent porosity with low particle packing in the clay bodies.

Firing temperature effect on compressive strength

Mechanical properties of the fired clay bricks play very important roles for their quality control. The worthy usages of bricks in structural and engineering applications depend mainly on their mechanical properties as well. Several standardized techniques were discussed for testing of the mechanical properties of ceramic bodies such as compressive strength (ASTM C1424-15, 2015), flexural strength (ASTM C1161-13, 2013) and static fracture toughness (ASTM C1421-16, 2016) and so on. However, measurement of the compressive strength is one of the most reliable techniques and is generally used for brittle and thick clay brick samples to assess their quality control.

Figure 5 shows the result of the estimated compressive strength of nine clay brick samples fired at different firing temperature. It is clear from the figure that the NB-FPr, i.e., the fired clay brick sample produced by the brick factory of Kathmandu valley using firing kiln of the brick factory, shows the maximum compressive strength of 17.55 MPa than the compressive strength of other eight clay brick samples
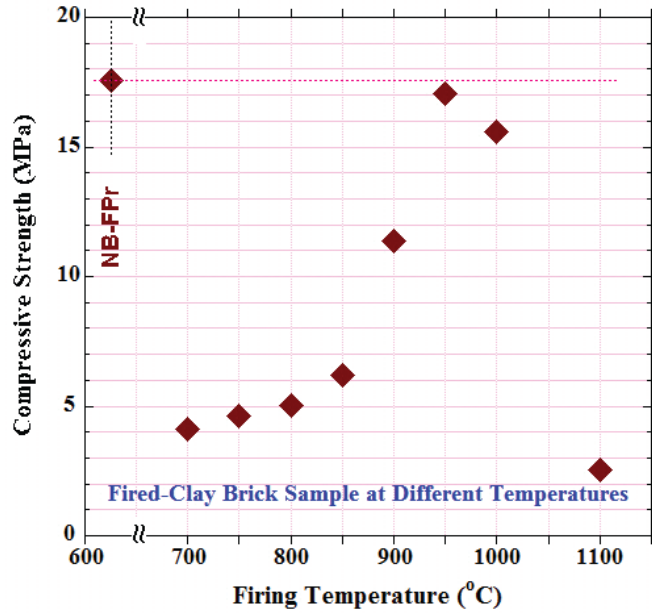

Fig. 5. Firing temperature effect on the compressive strength of the fired clay brick samples

Table II. Compressive strength of the fired brick samples at different temperatures

Samples	Firing temperature (°C)	Compressive strength (MPa)
NB-700	700	4.12
NB-750	750	4.61
NB-800	800	5.01
NB-850	850	6.17
NB-900	900	11.37
NB-950	950	17.06
NB-1000	1000	15.60
NB-1100	1100	2.55
NB-FPr	Factory produced	17.55

fired in the temperature range between 700° to 1100° C. The compressive strength of the fired clay brick samples used in this study is gradually increased with increasing the firing temperatures from 700° to 950° C and it was found to be maximum compressive strength of 17.06 MPa at 950° C as shown in Fig. 5. However, further increasing the firing temperature to produce the clay brick samples at 1100° C, the compressive strength is significantly decreased to very low value of about 2.55 MPa for NB-1100 brick sample as shown as well as in Fig. 5 and also in Table II.

Consequently, it can be said that the sintering mechanism of the clay brick sample at 700° to 950° C firing temperature should be different than at 1000° C or high firing temperature. The dependence of the compressive strength on the firing temperature of clay brick materials does not exhibit a significant increase of the compressive strength at 1100° C. At high firing temperature of 1100° C, the compressive strength decreases significantly due to the softening of the clay brick materials and the formation of melt. The similar behavior was reported for aluminium oxide where the flexural strength was decreased with increasing the firing temperatures above 1000° C, nevertheless, mullitic materials exhibited a maximum level of flexural strength at high temperatures (Urbánek *et al.*, 2017).

The sintering processes of brick clay powders can be divided into two types: solid-state sintering at low firing temperature range and the liquid phase sintering comparatively at high temperature range as described elsewhere (Kang, 2005). The decrease of the mechanical strength as well as the physico-chemical properties of the electro-ceramic materials consisted of kaolin, aluminium oxide and feldspars was also reported by different research groups (Urbánek *et al.*, 2017; Trnik *et al.*, 2013; Stubna *et al.*, 2009; Traore *et al.*, 2001). The NB-900, NB-950 and NB-1000 fired brick samples at 900°, 950° and 1000° C show the compressive strength of 11.37, 17.06 and 15.60 MPa, respectively, and remaining other five brick samples of NB-700, NB-750, NB-800, NB-850 and NB-1100 show the compressive strength less than 10 MPa. Furthermore, the CS of the brick sample fired at 950° C is estimated almost same value as that of the factory produced brick sample, i.e., NB-FPr. These results revealed that the most suitable firing temperature to produce best quality of the clay brick sample using the raw clay raw materials of the brick factory of Kathmandu seems to be about 950°-1000° C.

Relation between physical properties and compressive strength

There is a good correlation between the compressive strength with all these three types of physical properties (i.e., water absorption capacity, apparent porosity and bulk density) of the entire analyzed clay brick sample specimens fired between 700° to 1000°C temperatures as shown in Figs 6-8. The compressive strength at different firing temperatures of the clay brick samples is found to be increased exponentially with decreasing of water absorption capacity and apparent porosity as depicted in Figs 6 and 7, respectively, although the compressive strength of the clay brick samples is exponentially increase with slight increase of their bulk density as shown in Fig. 8. Consequently, in order to improve the mechanical properties of the clay brick bodies, it can be said that the efforts need to focus on decreasing both the water absorption capacity and apparent porosity, and on increasing the bulk density as well, because these physico-sintering properties are responsible for the production of better quality clay brick samples and other ceramic bodies too. Moreover, figures 6-8 clearly show a good correlation between the compressive strength of the fired clay bricks with water absorption capacity, apparent porosity and bulk density, respectively. On the other hand, the compressive strength of the fired clay brick samples used in this study is directly correlated with the firing temperature as shown above in Fig. 5 and also summarized in Table II.
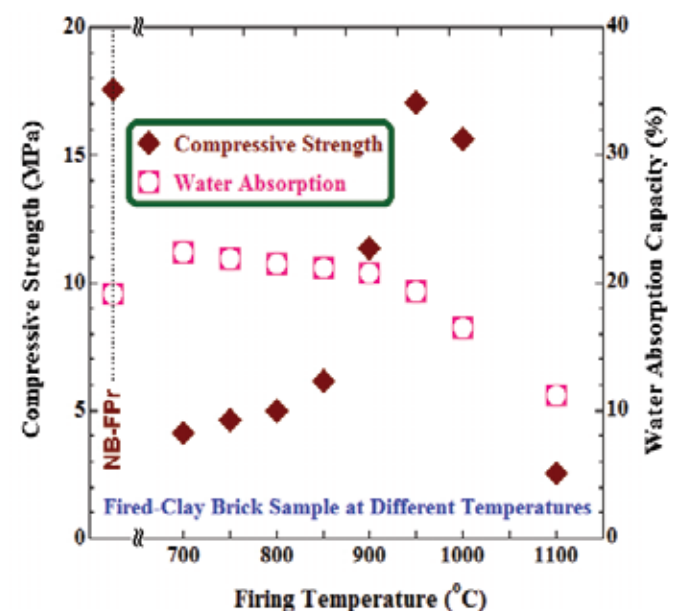

Fig. 6. Temperature effect on the compressive strength and water absorbtivity of the fired clay bricks
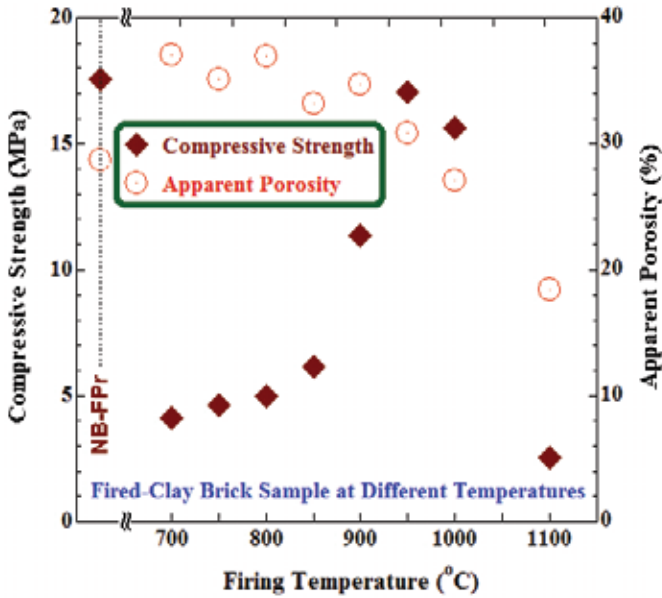
Fig. 7. **Temperature effect on the compressive strength and apparent porosity of the fired clay bricks**
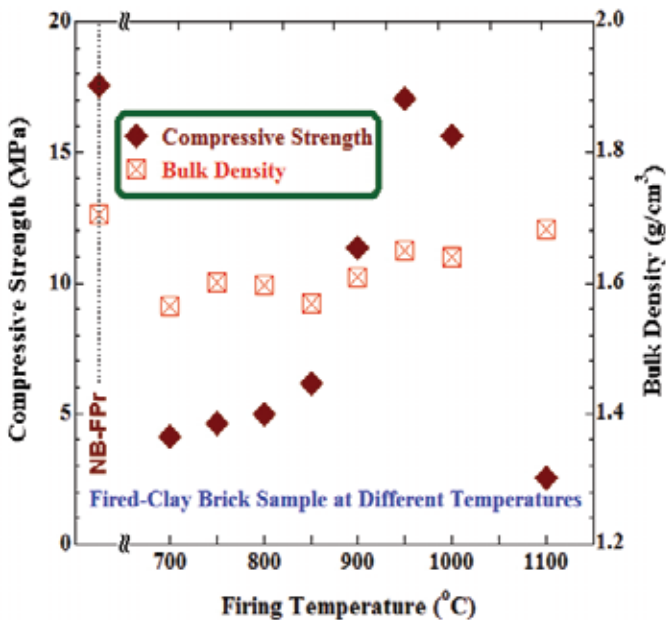

Fig. 8. **Correlation between the compressive strength and bulk density of fired clay bricks**

Conclusion

The present research work was focused to study the firing temperature effects on three different types of physico-sintering properties: water absorption capacity, apparent porosity and bulk density and one mechanical property, i.e., compressive strength of twenty seven clay brick sample specimens using ASTM standards. Following conclusions are drawn from the results and discussion.

i. The water absorption capacity and apparent porosity of the fired clay brick samples is found to be decreased, although the bulk density is increased with increasing the firing temperature in the range of 700° to 1100° C.

ii. The bulk density of the fired clay brick samples is found to be increased from 1.54 to 1.77 g/cm³ with decreasing their water absorption from 25 to 11 % and the apparent porosity from 39 to 16 % as a function of firing temperature in the range of 700° to 1100° C.

iii. The most suitable firing temperature for producing of the better quality clay brick samples by local brick factory of Kathmandu valley seems to be in the range of 950°-1000° C at which the maximum compressive strength of the bricks is reported in the range of 11 to 17 MPa.

iv. The compressive strength of the clay brick samples is found to be increased exponentially with decreasing the water absorption capacity and apparent porosity.

v. The physical properties are largely responsible for the betterment of the mechanical properties of the structural brick samples of Kathmandu valley and hence efforts need to focus on decreasing both water absorption capacity and porosity with increasing density in order to improve the compressive strength property.

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