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Investigation on Physico-Sintering and Mechanical Properties of Clay Tiles Available in Kathmandu Valley of Nepal

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Physico-sintering and mechanical properties of 37 contemporary and ancient tiles of Kathmandu valley consisting of quartz, feldspars, spinel, mullite and hematite were studied using ASTM standards. Most of the tiles samples, *i.e.*, about 73 % of the total tiles used here, have the water absorption and the apparent porosity in the range of 10-20 % and 20-35 %, respectively, while the bulk density of all the tile samples is found to be in the range of 1.5-2.2 g/cm^3. The bulk density of the tile samples is found to be increased with decreasing the water absorption and apparent porosity. Most of the tile samples analyzed in this study showed the flexural strength in the range of 10-30 MPa. The flexural strength of all the clay tile samples is found to be decreased exponentially with increasing the physico-sintering properties. Consequently, durability of the tiles is directly influenced by their physico-sintering properties.

Keywords: Tiles, Density, Flexural strength, Water absorption, Porosity, ASTM standards.

INTRODUCTION

Usages of various ceramic products have been recently attracted more attention than the counterpart of metallic and polymeric materials in scientific community [1,2], because the ceramic products have advantageous physical, chemical, refractoriness, strength retention at high temperature, high melting point and good mechanical properties [3-5]. Early evidence of the uses of the clay-based ceramic products was found in Harappan, Chinese, Greek civilizations, *etc*. [3,5]. For example, it was reported that the glazed tile was used to decorate the wall of the famous Tower of Babel and the Ishtar Gate in the ancient City of Babylon about 562 BC [3].

Clay tiles are generally used as coverings for floor, wall, facade or roof and can ranges from simple square tiles to complex mosaics and they are generally classified into six different types depending on their water (moisture) absorption capacity as well as their shaping or production methods. They are fully vitrified also called porcelain tile, semi-vitrified, terracotta, glazed porous, glazed vitrified and mosaics tiles [6]. However, all types of these clay tiles should be durable, rigid, hygienic, non-combustible and fire resistant with relatively low resistance to shock with high mechanical strength.

Different clays and admixtures are the principal raw materials for manufacturing various types of the clay tiles [7]. Content of water and dispersion of the solid phase of these clay raw materials used for the production of the clay tiles should be optimized taking into account subsequent drying and sintering to ensure the maximally high parameters of the tile production. On the other hand, the mineralogical phase composition of the raw materials used for the production of clay tiles is one of the main indicators of components selection for its final products. For example, the refractoriness and mechanical strength of the clay tiles could be increased with increasing the Al_2O_3 and the SiO_2 contents [7]. High amounts of Fe_2O_3 and TiO_2 in the raw materials of the tile products may reduce their quality but offer higher plasticity as well as the mechanical strength and they also affect colour of the burnt ceramic bodies at high firing temperatures. The Fe_2O_3, MgO, Na_2O, K_2O and CaO are considered as flexing agents and can influence the densification behaviour of the ceramic tiles during the firing process [8]. Important source of these fluxing oxides are different feldspars and the presence of high amounts

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of fluxing components in the clay tile body permit a lowering of its firing temperature [8-10]. It was investigated the effect of the particle size distribution of feldspar on the formation of pores in the green compact and the final clay ceramic products [10].

The physico-sintering (*i.e.*, water absorption, porosity, bulk/apparent density *etc.*) properties of the tile bodies are generally correlated with their mechanical properties [9]. The water absorption capacity of the tiles is one of the important criteria for representing their quality and strength. A lower value of the water absorption is always desired for good quality of clay tiles. The differences in chemical or/and mineralogical behaviour of the raw materials of the tile bodies, no doubt controls the water absorption capacity and the low water absorption value of the ceramic bodies should be due to the presence of high amounts of clay minerals content in their compositions with high densification, low porosity and high bulk density. Furthermore, porosity of the clay tiles also affects their mechanical properties as well as the water absorption/bulk density. It is understandable that the porosity of the ceramic bodies is associated with inferior quality, because high porosity and surface pores create the same problems in mechanical properties of the bodies. It was reported that the Young's modulus of porcelain was decreased with increasing porosity [11] and specimens with small pores were found to have a higher Young's modulus than specimens with large pores at equivalent porosities [12]. The effect of MgO/CaO ratio on the microstructure of glazed floor tiles was evaluated using different analytical techniques and the results indicated that the higher amounts of α-cordierite crystalline phase which was observed at the temperature range of 1160 to 1190 °C showed the highest micro-hardness of the tile samples [13]. On the other hand, it was reported that the flexural strength and abrasion resistance of porcelain tiles were enhanced due to the formation of mullite and kyanite [14]. It is also equally important to acknowledge that inferior clay tile quality is not one that simply has high porosity, but the number and size of surface pores is equally important.

However, the chemico-sintering and mechanical properties of different types of clay tiles available in local market of Kathmandu valley are not reported much in the scientific community of Nepal. A large number of clay tile dealers were reported in Kathmandu valley [15,16], although the consumers are mostly concerned with price and less concerned with quality and the physico-sintering and mechanical properties of the clay tiles. Considering these facts behind the quality and properties of clay tiles available in Kathmandu valley, the present research work was focused to estimate the most important physico-sintering properties of water absorption, apparent porosity and bulk density and the mechanical property of flexural strength of different clay tile samples using ASTM standards and also to correlate between these physico-sintering and mechanical properties.

EXPERIMENTAL

Different types of clay tiles are mostly used in houses, temples, stupa, shopping centres, hospitals and schools for covering roof, floor, wall, shower or tabletop, *etc.* in urban areas of Nepal like Kathmandu valley. However, most of these tiles are used in very small amounts in rural areas of the Nepal. So the targeted tile sample collection areas to carry out the present research work were of the Kathmandu valley.

Altogether 37 clay tile samples of different brands available in the local market of Kathmandu valley were collected to carry out the present research work. Among these 37 tile samples, 35 are of the contemporary wall and floor clay tiles and remaining two samples are of an ancient floor tiles from two famous historical temple sites of Kathmandu valley. Three sample specimens of each type of the collected clay tiles were prepared for analysis of their physico-sintering properties of water absorption, apparent porosity and bulk density and mechanical property of the flexural strength. Mineralogical phase characterization of these clay tile samples used in the present research work was analyzed using X-ray diffraction and Fourier transform infrared spectroscopic techniques and the phases of quartz, feldspars, spinel, mullite and hematite were confirmed in these fired-tile bodies [17].

The physical properties (*i.e.*, water absorption, apparent porosity and bulk density) of the clay tile specimens were estimated using following relation in accordance with the ASTM standards [18] as shown below in eqns. 1-3:

$$\text{Water absorption (\%)} = \frac{S-D}{D} \times 100 \qquad (1)$$

$$\text{Apparent porosity (\%)} = \frac{S-D}{V} \times 100 \qquad (2)$$

$$\text{Bulk density (g/cm}^3) = \frac{D}{V} \qquad (3)$$

where, D is the dry weight of sample, S is the saturated weight of the sample and V is the exterior volume of the ceramic tile specimen.

The flexural strength of 13 tile samples was estimated using flexure test machine available at Central Material Testing Laboratory, Department of Civil Engineering, Pulchowk Engineering Campus, Tribhuvan University, Lalitpur in accordance with the ASTM standards using eqn. 4 [19].

$$\text{Flexural strength } (\sigma) = \frac{3 \times L \times F}{2 \times b \times d^2} \qquad (4)$$

where, L is specimen length, F is total force applied to the specimen, b is specimen width and d is specimen thickness.

RESULTS AND DISCUSSION

Physico-sintering properties of clay tiles: The increasing demand of the clay tiles has led to develop their good quality day by day and hence the cost-effective and acceptable optimized methodology for the production of different types of tiles are highly desirable. The physico-sintering and mechanical properties of the clay tiles depend on the optimum conditions maintained at the time of their manufacturing. Some basic physico-sintering properties such as water absorption, bulk density and apparent porosity, flexural and compressive strengths act as the quality control parameters of the clay bodies, which ultimately depend on the phase and chemical compositions of their raw materials.

Fig. 1 shows the changes in the water absorption capacity of the collected 37 clay tile samples from Kathmandu valley with three tile specimens of each tile samples. It is clearly observed from the figure that about 86.5 % (*i.e.*, 32 tile samples except five tile samples) of the analyzed tile samples used to carry out this study show the water absorption capacity in the range of 10-25 % (Fig. 1), which is slightly lower water absorption capacity than that previously reported for brick samples of Kathmandu valley [20]. Only three samples; No. 2, No. 6 and No. 33 show the water absorption capacity less than 10 %, while tile samples No. 13 and 37 show more than 25 % of water absorption capacity as depicted in Fig. 1.

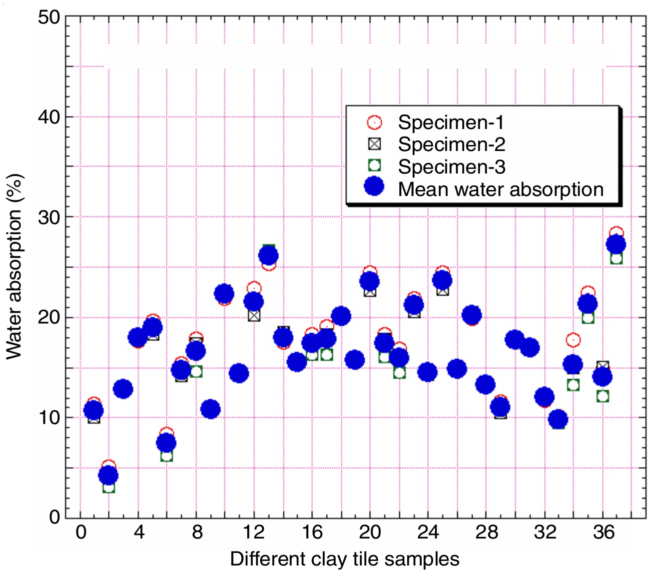

Fig. 1. Water absorption capacity of the collected clay tile samples

It is meaningful to mention here that the sample No. 33 and No. 34 are ancient floor tiles used in famous historical temples of Bhaktapur and Patan, respectively. The water absorption capacity of these two ancient floor tiles is found to be almost same as that in the contemporary tile samples of Kathmandu valley. These results revealed that most of the contemporary wall and floor tiles collected from the market of Kathmandu valley are of BIII type of the glazed porous tile having the water absorption capacity between 10-20 % [21] and these tiles are not frost resistance and is generally used in interiors above sub zero temperatures.

Fig. 2 shows the result of the estimated bulk density of all 111 clay tile specimens of 37 different types of collected tile samples from Kathmandu valley. It is clear from the figure that only 3 types of tile samples show the mean bulk density less than 1.6 g/cm^3, while remaining 34 types of tile (*i.e.*, about 92 %) samples show the bulk density in the range of 1.6-2.2 g/cm^3. It is generally considered that the clay tile samples having low water absorption capacity have high bulk density and expected high mechanical strength also. On the other hand, the apparent porosity of all the tile specimens is found to be in the range of 20-40 % except 4 types of tiles as shown in Fig. 3.

Furthermore, there is a direct correlation between the water absorption capacity as well as the apparent porosity with the bulk density of all measured tile samples used in this study.

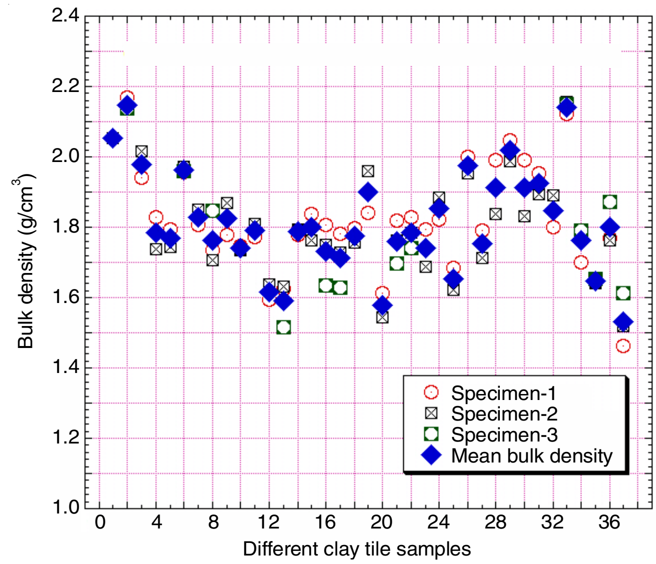

Fig. 2. Bulk density of the collected clay tile samples

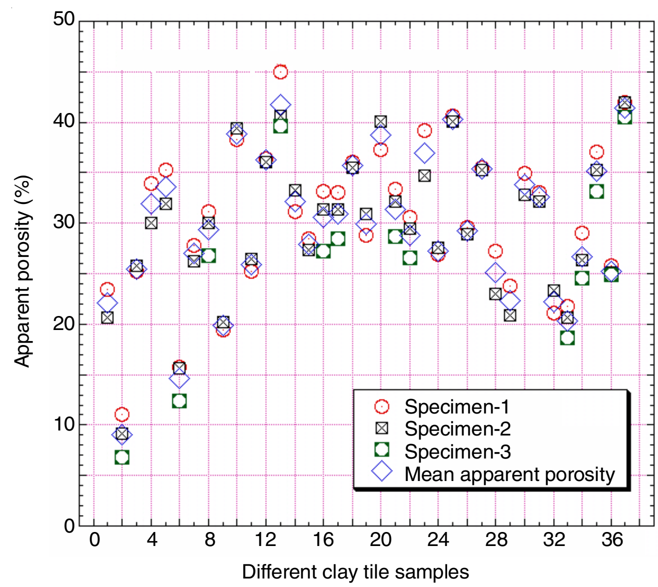

Fig. 3. Apparent porosity of the collected clay tile samples

The bulk density of the tile samples is increased with decreasing both the water absorption capacity as well as the apparent porosity as shown in Fig. 4. It is meaningful to mention here that the densification behaviour in term of the bulk density is a function of firing temperature of the ceramic bodies like clay tile and the densification of the tile samples reaches the maximum values at high temperature. The low density value observed for the specimens at lower temperatures are directly related to their high apparent porosity with low particle packing.

Mechanical property of clay tiles: Estimation of the mechanical propriety of the clay tile samples plays very important role for their quality control study and reliable usages in structural and engineering applications. Several standardized techniques are discussed for testing the mechanical properties of ceramic bodies such as flexural strength [19], compressive strength [22] and static fracture toughness [23], *etc*. Present study was focused to estimate of the flexural strength of total thirteen tile samples including two ancient floor tiles (*i.e.*, TA-33 and TA-34) among the collected 37 types/brands tiles from

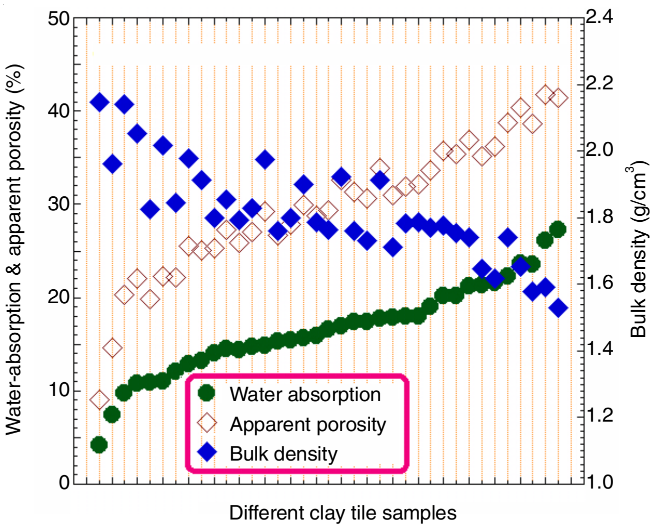

Fig. 4. Relation between the water absorption as well as apparent porosity with the bulk density of the collected clay tile samples

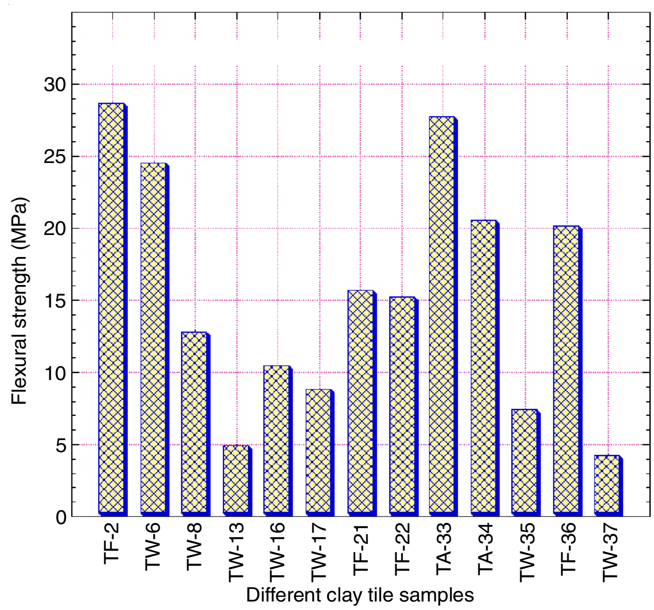

Fig. 5. Flexural strength of the collected clay tile samples

the local vendors of Kathmandu valley and the obtained results are discussed here.

It is clear from the Fig. 5 that two tile samples of TW-2 and TA-33 show the flexural strength more than 25 MPa and the TW-2 sample shows the maximum flexural strength of 28.76 MPa. Most of the tile samples (*i.e.*, nine tiles), used in this study, show the flexural strength between 10-30 MPa and remaining four tile samples show the flexural strength less than 10 MPa; particularly the TW-13 and TW-37 wall tiles show 5 MPa or less as shown in Fig. 5 and also tabulated in Table-1.

These results revealed that all the floor tile samples including both the contemporary and ancient tiles used in this study, show the high flexural strength of 15 MPa or high, while the flexural strength of all most all the wall tiles except one (*i.e.*, TW-8) show less than 10 MPa. High mechanical strength of the ceramic bodies is mainly due to the presence of mullite, residual quartz and its particle size. However, the mechanical strength of the ceramic body was found to be deteriorated in presence of undesirable phases like calcite in raw clay minerals of the ceramic body [24-26]. Therefore, it is assumed that different types of the mechanical strength of the fired ceramic bodies depend on their composition and void developed at high firing temperature [27].

The pore or void space exists between the powder particles of the clay raw materials by subsequent compaction to obtain the desired shape. Most of these pores or voids can be eliminated at high firing temperatures. However, it is often the case that the pore elimination process is incomplete and some residual pores remained. Any residual pores have a deleterious influence on the mechanical properties like compressive strength, flexural strength, *etc*. On the other hand, both the porosity and water absorption properties of clay tiles are deleterious to the compressive strength as well as the flexural strength for two reasons: (1) pores reduce the cross-sectional area, across which a load is applied and (2) they also act as stress concentrators; for example, an applied tensile stress is amplified by a factor of 2 for an isolated spherical pore [28].

The influence of porosity on strength is rather dramatic; for example, it is not uncommon that 10 % volume porosity will decrease the flexural strength by 50 % from the measured value for the nonporous materials. Experimentally, it was reported that the flexural strength decreased exponentially with volume fraction porosity (P) as give by following equation [29].

TABLE-1
FLEXURAL STRENGTH AND PHYSICO-SINTERING PARAMETERS OF THE CLAY TILE SAMPLES

Tile numbers	Sample name	Types of tile	Water absorption (%)	Apparent porosity (%)	Bulk density (g/cm^3)	Flexural strength (MPa)
2	TF-2	Floor	4.20	9.03	2.15	28.76
6	TW-6	Wall	7.46	14.58	1.96	24.64
8	TW-8	Wall	16.65	29.31	1.76	12.91
13	TW-13	Wall	26.10	41.76	1.59	5.00
16	TW-16	Wall	17.40	30.61	1.73	10.46
17	TW-17	Wall	17.90	30.96	1.71	8.82
21	TF-21	Floor	17.43	31.38	1.76	15.68
22	TF-22	Floor	15.95	28.83	1.78	15.19
33	TA-33	Ancient	9.78	20.35	2.14	27.71
34	TA-34	Ancient	15.33	26.68	1.76	20.65
35	TW-35	Wall	21.35	35.17	1.65	7.33
36	TF-36	Floor	14.04	25.27	1.80	20.12
37	TW-37	Wall	27.26	41.46	1.53	4.27

$$\text{Flexural strength } (\sigma) = \sigma_0 \times \exp(-nP) \quad (5)$$

where, σ_0 and n are experimental constants.

It is generally considered that low mechanical strength of the ceramic bodies like clay tiles is also related with their physico-sintering properties like high water absorption capacity, low bulk density and high apparent porosity. There is a good correlation between the flexural strength with all these three types of physico-sintering properties of all the analyzed tile samples used in this study as shown in Figs. 6-8. The flexural strength of the tile samples is found to be decreased exponentially with increasing the water absorption capacity and apparent porosity as shown in Fig. 6, although the flexural strength of the samples is increased with increasing their bulk density as shown in Fig. 7.

The compressive strength of the brick samples is directly related with the bulk density. Consequently, it can be said in order to improve the mechanical properties of the clay tiles, efforts need to focus on decreasing both the water absorption

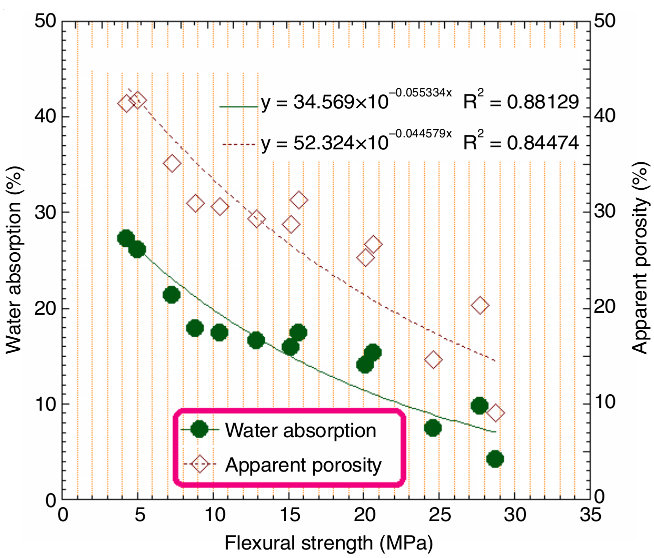

Fig. 6. Influence of the water absorption and apparent porosity on the flexural strength of the collected tile samples

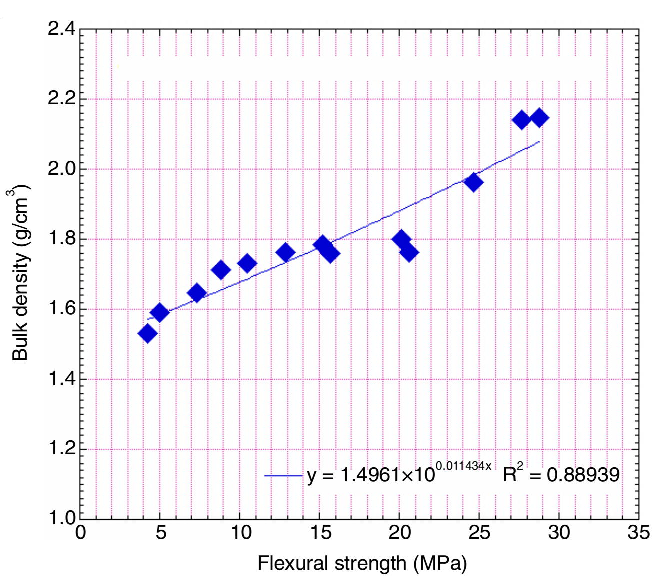

Fig. 7. Influence of the bulk density on the flexural strength of the collected tile samples

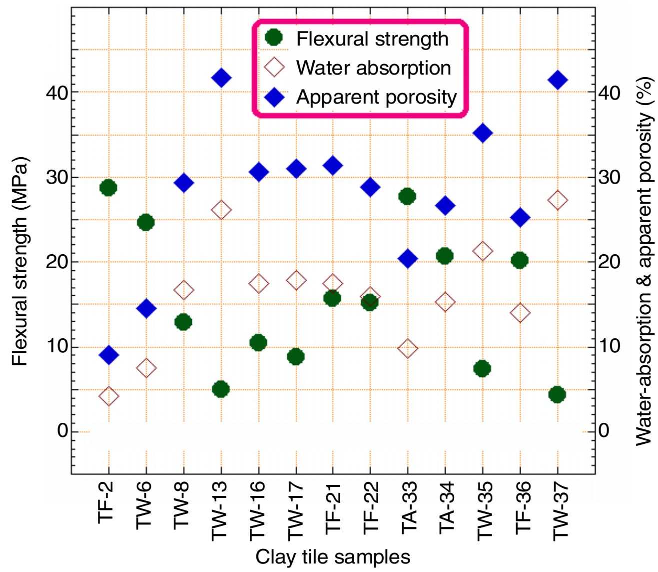

Fig. 8. Correlation between the flexural strength, water absorption and apparent porosity of the collected tile samples

capacity as well as the apparent porosity and on increasing the bulk density also, because these physico-sintering properties are largely responsible for the betterment of the clay tiles and other ceramic bodies. Similarly, a good correlation between flexural strength, water absorption capacity and apparent porosity of the tile samples was shown in Fig. 8 and also tabulated in Table-1. In general, the tile samples which have 10 % or less water absorption capacity and 25 % or less apparent porosity show the compressive strength of more than 25 MPa.

Conclusion

The present research work was focused to investigate the physico-sintering and mechanical properties of 37 different types/brands of tile samples collected from local vendors of Kathmandu valley and historical temple sites for their quality assessments using ASTM standards and following conclusions are drawn.

• Most of the contemporary tile samples are of the glazed porous BIII type having the water absorption capacity between 10-25 % and could be safely used in interiors above sub zero temperatures.

• The bulk density of the tile samples is found to be increased from 1.5 to 2.2 g/cm^3 with decreasing their water absorption capacity and apparent porosity.

• Both the contemporary and ancient floor tiles showed the high flexural strength of 15 MPa or high, while most of the wall tiles showed the flexural strength less than 10 MPa.

• The flexural strength of the tile samples is found to be decreased exponentially with increasing both the water absorption capacity and apparent porosity.

• The water absorption, apparent porosity and bulk density are largely responsible for the betterment of the tiles and hence efforts need to focus on decreasing both the water absorption capacity and apparent porosity with increasing the bulk density in order to improve the mechanical properties of the tiles.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interests regarding the publication of this article.

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