ESTIMATING RESIDUAL STRESS IN GLAZED CERAMIC TILE

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ABSTRACT

Glazed ceramic wall tiles have been used for a long time all around the world. During the manufacturing process, the difference between the thermal expansion coefficient of the glaze and body during cooling in the kiln is the cause of residual stress and also curvature of the tile.

These residual stresses in combination with stresses applied in service can sometimes cause faults to appear.

Therefore, estimation and prediction of residual stress is of great importance especially in designing new materials and also improving the quality of products.

Hence, in this study, the validity of the Timoshenko model (presented for two-layer elastic materials) and also FEM analysis has been confirmed for fast double-fired glazed ceramic wall tiles. This is verified by the good agreement observed between the results of the experimental curvature measurements and corresponding values from the models.

The study of different samples by the SEM method and also autoclave test results have indicated the destructive effects of residual tensile stress in the body-glaze interface.

Subsequently, the residual stress distribution in layers was also studied; the influence of glaze thickness and thermal expansion was determined. Considering a glaze with lower thermal expansion than that of the body, it is observed that lowering the glaze thickness will increase compressive stress in the glaze and decrease tensile stress in the interface.

Furthermore, the greater difference between the thermal expansion of the glaze and body has led to simultaneous increase of tensile stress in the interface as well as compression in the glaze.

Therefore, it is possible to achieve a glaze layer containing some compressive residual stress, while minimizing tensile stress at the interface, by choosing optimum materials properties and manufacturing process variables.

1. INTRODUCTION

The industry of ceramic tile, which goes back thousands of years, is rooted in ancient civilization. Thanks to the brilliant history, as well as the advantages of rich mines and also inexpensive labour and energy, the Iran tile industry has grown significantly over the last 10 years. Thus, in the year 2002, it ranked 9th among the top ceramic tile producers in the world [1].

Fast double-fired glazed wall tile, is one of the leading products in the industry. Through the manufacturing process, due to the difference in the thermal expansion coefficient (TEC) of the glaze and body, some stresses arise and develop within these two layers during the firing process. Meanwhile, below the temperature at which the glaze solidifies and becomes rigid during the cooling process, these stresses remain in the form of residual stress in the final product [2],[3].

If the TEC of the applied glaze is less than that of the body, more shrinkage of the body puts the glaze under compression and develops the stress in both layers during cooling. Therefore, the tile bends to minimize the mentioned stresses; hence the piece contains convex curvature.

In contrast to the aforementioned conditions, concave curvature of the final piece as well as residual tensile stress within the glaze will occur when applying a glaze with a higher TEC than the body [4].

In addition to the TEC of two layers, the amount of residual stress as well as the curvature of the tile depends upon some other factors such as modulus of elasticity, thickness and thermal conductivity of the two layers and also the cooling schedule[5],[6].

In order to prevent crazing caused by moisture expansion owing to the porous earthenware body of double-fired wall tiles, a glaze with a TEC less than that of the body is usually applied.

Considering these criteria, the stress originated from the TEC difference between the two layers is added to curvature-induced stress, which gives rise to the residual stress distribution profile indicated in Figure 1.

As a result, the glaze layer contains compressive stress and the body includes the maximum tensile stress at the interface with the glaze while the bottom of the body contains some compressive residual stress [7],[8].

It has been observed in many cases that the mentioned residual tensile stress of the interface when added to the applied stress causes some damage to the piece during service.

For example, a simple impact or any other mechanical shock may give rise to tile fracture as well as tile breakage during cutting for installation, and also damage due to thermal shock (even during third firing). We may also note tile crazing due to moisture expansion [7].

Therefore, prediction of the residual stress profile in a ceramic tile as well as studying the effects of material properties and manufacturing process variables are of paramount significance, especially in designing new products.

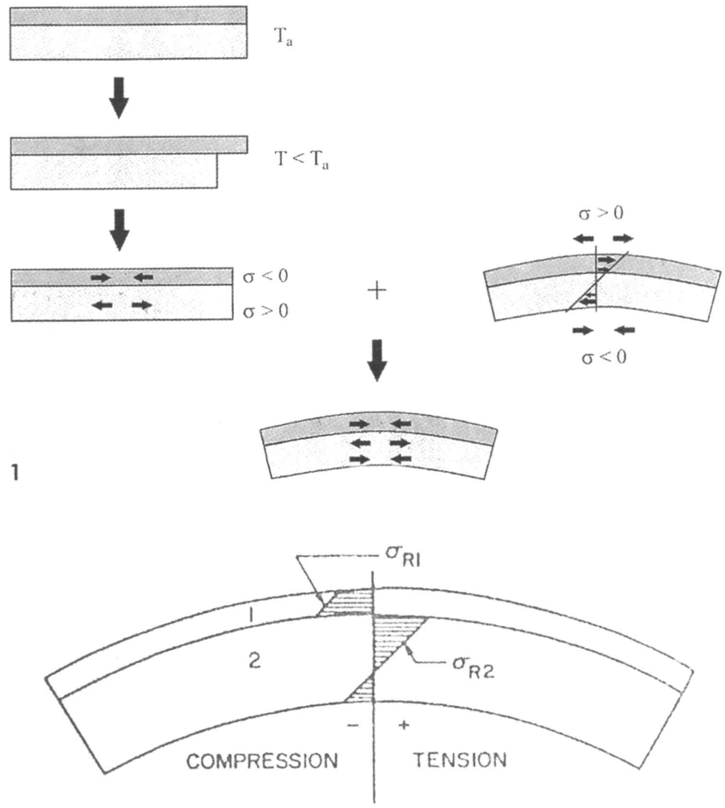


Figure 1. Residual stress profile originating from the TEC difference of the two layers

There are various methods for determining residual stress in materials, but the limitation and problems concerning their application to glazed ceramic tiles lead us to apply a model known as the Timoshenko model designed for two-layer elastic materials [10].

Through verifying the validity, and in fact confirming the applicability of the Timoshenko model for fast double-fired glazed wall tiles, we can use this model for estimating the type, magnitude and distribution of residual stress in the tile [8],[9].

According to the mentioned model, the residual stress caused by the TEC difference of two-layer elastic materials may be calculated from the following equations [6]:

$$\sigma_B = \left[\frac{K_R}{h}\left(y - y_0\right) + \frac{mn}{1+mn}\right] E_B \Delta C \qquad (1)$$

$$\sigma_T = \left[\frac{K_R}{h}\left(y - y_0\right) - \frac{1}{1+mn}\right] n.E_B.\Delta C \qquad (2)$$

Where:

$$K_R = \frac{6(m+1)^2 mn}{m^4 n^2 + 4m^3 n + 6m^2 n + 4mn + 1}$$

σ_B = stress in base layer (body)
σ_T = stress in top layer (glaze)
h = tile thickness (m)
y_0 = position of neutral axis
h_t = top layer thickness (m)
h_b = base layer thickness (m)
m = h_t / h_b
E_b = base layer Young's modulus (kg/cm^2)
E_t = top layer Young's modulus (kg/cm^2)
n = E_t / E_b
ΔC = Difference in thermal expansion between the top and base layer

The curvature (D) can be determined from the following equation [5]:

$$D = \frac{l^2}{8h} K_R . \Delta C \qquad (3)$$

Moreover, we can use the Finite Element Method (FEM) to evaluate the effects of materials properties, design, and processing variables on residual stress in a ceramic tile.

FEM is a generic term for the numerical simplification of complex structure into a number of elements which, when solved simultaneously, can provide an accurate solution.

Using one of the widely used FEM commercial software packages (ANSYS) for modelling a glazed ceramic tile, simulating body and glaze layer as several elements with identical characteristics will be possible. Thus, the stress profile in every single element of the ceramic tile can be estimated when applying a known thermal or mechanical stress on the piece [9].

2. EXPERIMENTAL WORK

2.1. PREPARING THE TEST SPECIMENS

An industrial spray-dried powder formulated according to Table 1, containing approximately 6% moisture content was used for forming the 20x20 cm specimens by an industrial hydraulic press applying 300 kg/cm^2 pressure. The chemical analysis of the body is shown in Table 2.

Firing was performed in a roller kiln to a maximum temperature of 1140°C.

It is worth mentioning that in order to minimize the processing variables and fabricate similar specimens, the pressed tiles were taken from a specific cavity and all were fired in the same identical part of each row through the kiln.

Moreover, the bulk density of the biscuit specimens was determined through weighing and measuring set dimensions; specimens whose bulk density was not similar to the mean value were discarded.

Kaolinitic clay	Illitic-Kaolinitic clay	Bentonite	Feldspar	Calcium carbonate
30	30	10	20	10

Table 1. Body formulation of ceramic tile (wt%)

SiO_2	Al_2O_3	Fe_2O_3	TiO_2	CaO	MgO	K_2O	Na_2O	LOI
62.96	13.94	2.11	0.24	5.95	0.83	3.32	1.08	8.63

Table 2. Chemical analysis of the base layer (tile body)

In addition, on measuring the curvature of biscuits, the similar ones were selected and the curvatures of each one were written down.

In the present study, the biscuit specimens were glazed in the following different ways:

- In order to study the influence of glaze thickness on tile curvature and residual stress, five different amounts of glaze (A) slip (Table 3) with 1.85 g/cm^3 density were applied onto the biscuits by the bell method. Thus, five different glaze thicknesses were obtained.
- Three different glaze composition (A,B,C) with different TECs were applied in the same thickness by spraying a slip with 1.85 g/cm^3 density in order to evaluate the influence of glaze TEC.
- To emphasize the critical importance of residual tensile stress through which the defects arise in the glazed tile, a kind of slip with a higher TEC than both the glaze and body ($\alpha_{0\text{-}550\,C} = 8.89 \times 10^{-6}/^{o}C$) was applied as an intermediate layer (engobe) between biscuit and glaze. Consequently, a three-layer piece with a tensile stress concentration in the engobe layer was obtained.

SiO_2	Al_2O_3	Fe_2O_3	ZnO	CaO	MgO	K_2O	Na_2O	PbO	Zr_2
53.79	8.87	0.15	5.42	9.80	1.12	4.55	3.14	6.07	0.07

Table 3. Chemical analysis of glaze (A)

All the glazed biscuits were fired in a roller kiln for 43 minute up to 1040°C according to a set industrial firing schedule (Figure 2).

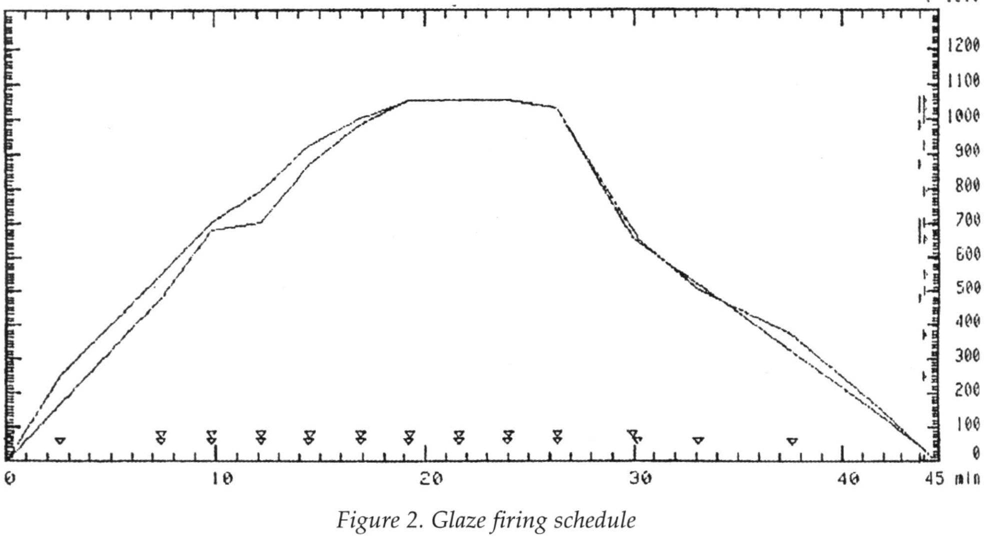


Figure 2. Glaze firing schedule

2.2. CHARACTERIZATION OF THE TEST SPECIMENS

The dilatometric test was run on test specimens made from engobe, glazes and body separately to determine the TEC of each material.

Young's modulus of the glazes was calculated, while that of the body was determined according to ASTM C674 determining the slope of the stress-strain curve obtained by 4-point bending strength analysis.

Using an optical microscope, the different applied thicknesses of glaze after firing were determined.

The curvature of the glazed and unglazed biscuit specimens was determined according to ASTM C485.

The ASTM C424 method was used to examine the crazing resistance of the glazed specimens.

Moreover, FEM modelling was performed through some simplifying assumptions. A 2-D cross section as representative of 3-D body and eight-noded element were considered. Curvature and also stress distribution in the glazed tile were estimated through simulating two-layer tile and applied thermal stress corresponding to the cooling profile of the firing process.

3. RESULTS AND DISCUSSION

Table 4 details the results of TEC (a) and Young's modulus (E) measurement for the body and three different applied glazes.

	$\alpha_{(0\text{-}550°C)}$ X10^{-6} / °C	E (GPa)
Biscuit	8.85	11.32
Glaze A	6.91	69.8
Glaze B	6.35	71
Glaze C	7.58	68.5

Table 4. TEC and Young's modulus of the biscuit and applied glazes

The thickness of the applied glaze layers after firing can be observed in Figure 3 and Table 5.

Glaze quantity applied on a biscuit (g)	50	70	100	150	200
Glaze thickness after firing (mm)	0.22	0.33	0.47	0.68	0.94

Table 5. Different glaze thicknesses resulting from applying different quantities (g) of glaze

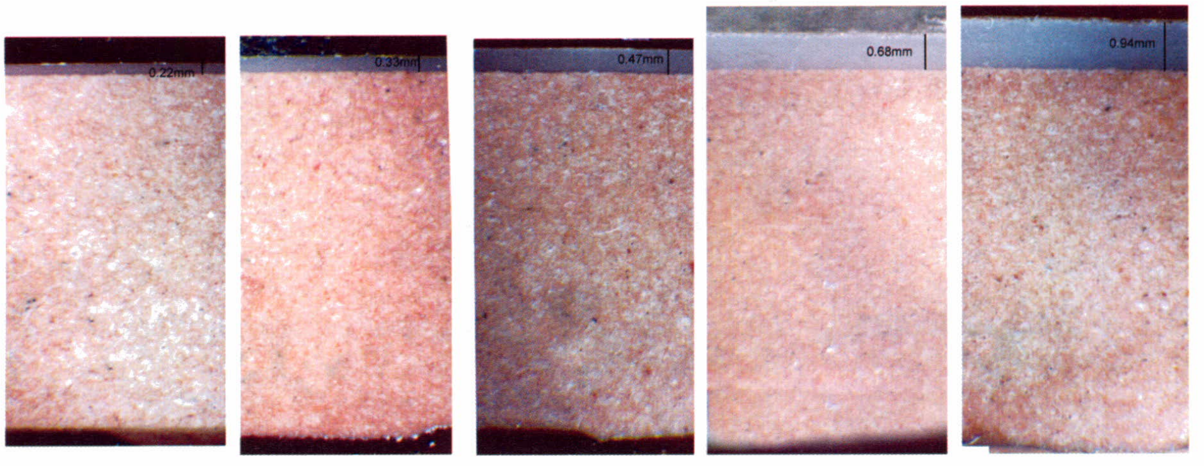


Figure 3. Optical microscopic picture of different glaze (A) thicknesses

It is to be noted that the solidifying temperature of the glaze (Ts), i.e., the temperature at which the piece begins to imprison the stresses inside, was considered 550°C according to Figure 4. This temperature is an important factor in calculating the differential contraction of two layers (ΔC), since:

$$\mathrm{dt}\,\Delta C = \int_{To}^{Ts} \left(\alpha_g - \alpha_b\right)$$

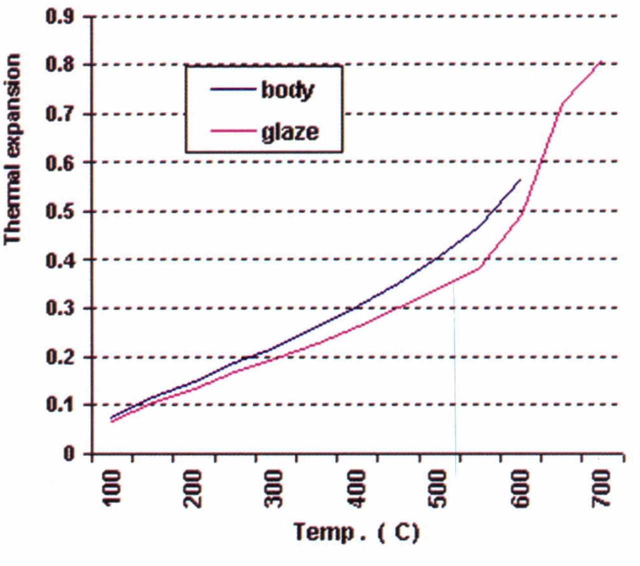


Figure 4. Dilatometric curve of body and glaze (A)

3.1. CURVATURE OF TILES WITH DIFFERENT GLAZE THICKNESS

Applying FEM simulation analysis (using ANSYS), the curvature profile variation caused by changing the glaze thickness can be obtained, as shown in Figure 5.

Table 6 corresponds to the curvature values resulting from the glost firing of tiles with different glaze thicknesses. The values related to the experimentally measured curvature are similar to the values calculated from the Timoshenko model as well as the FEM results.

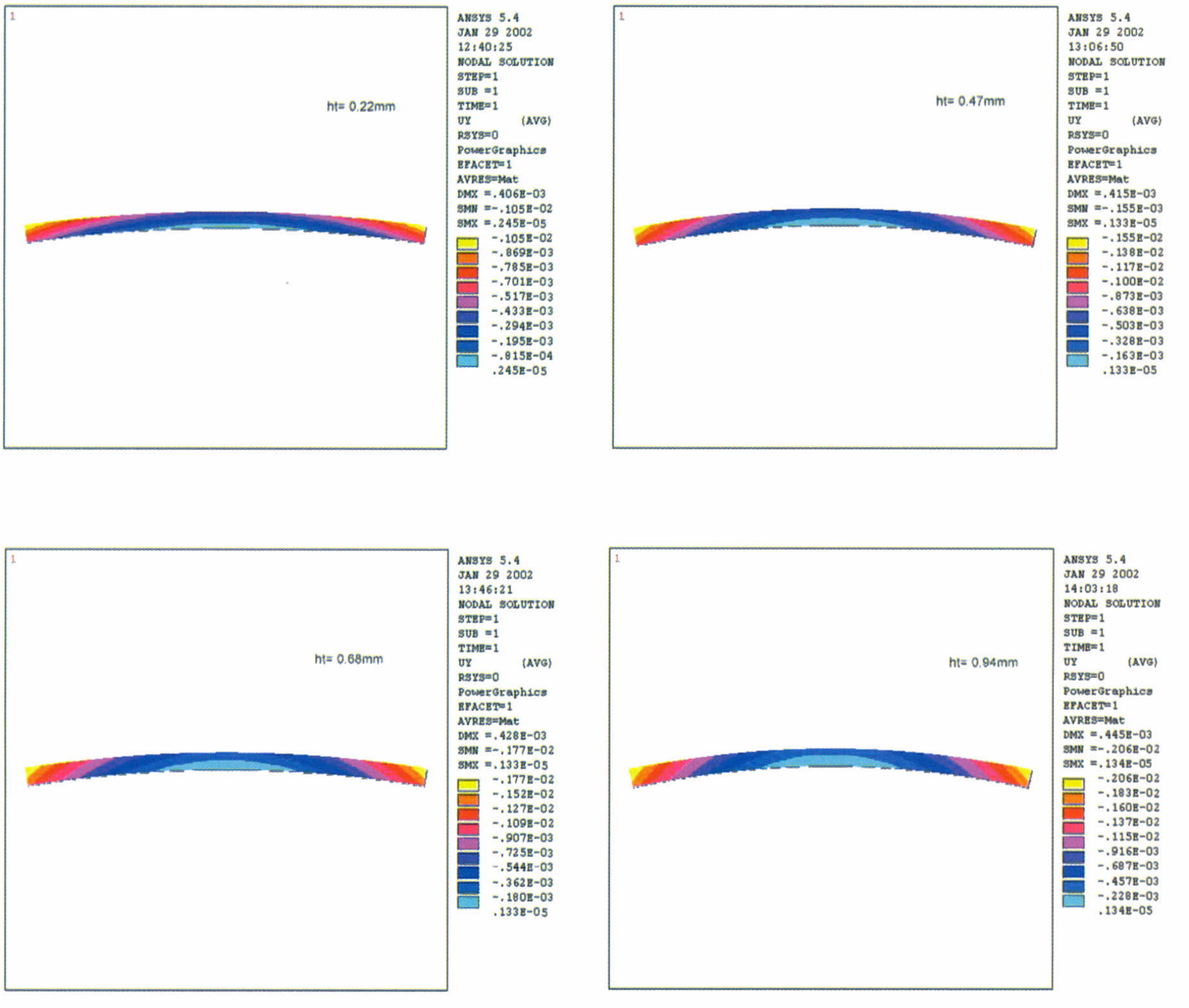


Figure 5. FEM results related to the curvature of tiles with different glaze thickness

Curvature Glaze Thickness (mm)	Exp. X 10^{-2} mm	Timoshenko X 10^{-2} mm	MEF X 10^{-2} mm
0.22	1.001	1.00	1.05
0.33	1.17	1.23	----
0.47	1.52	1.44	1.55
0.68	1.73	1.62	1.77
0.94	1.89	1.75	2.06

Table 6. Curvature of tiles with different glaze thickness

3.2. CURVATURE OF TILES WITH GLAZES OF DIFFERENT TECs

Table 7 presents the curvature values for tiles on which the glazes with different TECs were applied in the same thickness (0.28 mm).The results show good agreement between the results of the experimental measurement and the theoretical estimation.

Curvature Glaze Thickness (mm)	Exp. X 10^{-2} mm	Timoshenko X 10^{-2} mm	MEF X 10^{-2} mm
(A) 6.91	1.11	1.21	1.09
(B) 6.35	1.27	1.51	1.19
(C) 7.58	0.71	0.82	0.61

Table 7. Curvature of tiles with glazes of different TECs

Figure 6 highlights the variation of glazed tile curvature versus glaze thickness for three different applied glazes according to the Timoshenko equations.

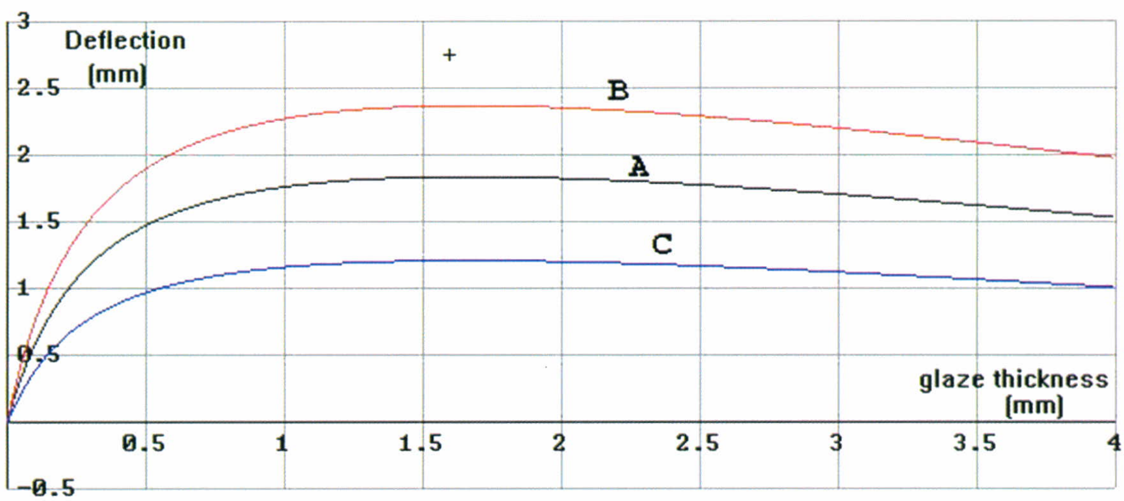


Figure 6. Glazed tile curvature versus glaze thickness (according to the Timoshenko model)

However, in practice, increasing the glaze thickness is limited. Hence, in this study a specific applicable range of glaze thicknesses is considered.

In general, the results confirmed the validity of the proposed Timoshenko equation (3) and FEM for estimating the glazed ceramic tile curvature, since there is good agreement between the results of the experimental method and the applied numerical analysis.

Therefore, considering the elastic behaviour of the thin glazes usually applied, the Timoshenko equation (1),(2) as well as FEM can be used to predict the type, magnitude and distribution of residual stress in fast double-fired glazed ceramic wall tile.

3.3. ESTIMATING THE RESIDUAL STRESS PROFILE IN THE GLAZED TILE

The residual stress profile involved in the discussed glazed tile, shown in Figure 7, is obtained as a result of replacing the characterized specifications of the two layers and processing parameters in the Timoshenko equation.

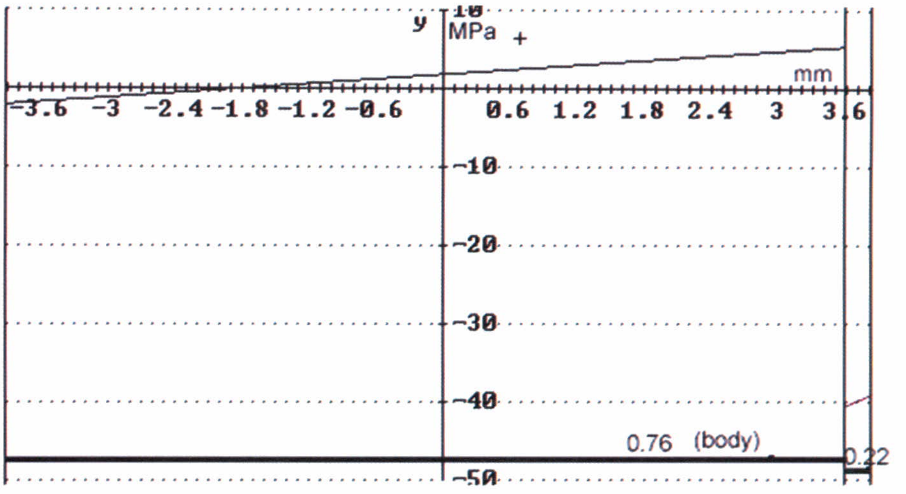


Figure 7. Residual stress profile in the specified glazed tile (according to the Timoshenko model)

As set out in previous works, when applying a force to a tile, the maximum tensile stress does not occur at the tile surface but at a distance from the surface[6].

As a result, the body interface with the glaze is expected to be a critical area or it may be considered a failure point, where the tensile residual stress as well as the tensile stress caused by impact tends to be the largest.

Fractography of the glazed tile fracture section, caused by impact, shows the fracture line through the interface (Figure 8).

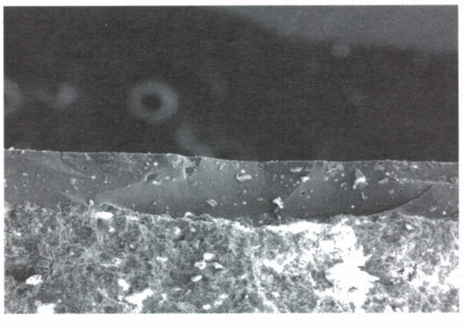
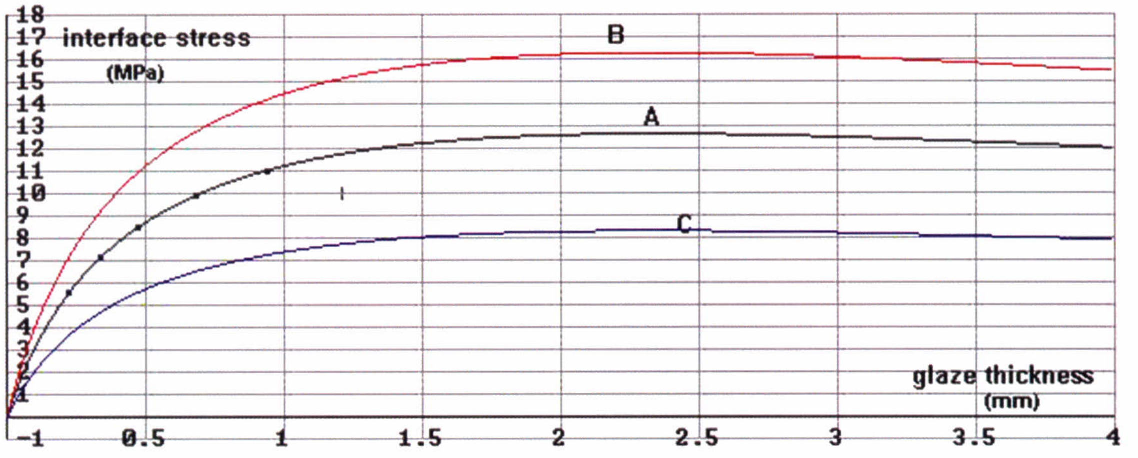


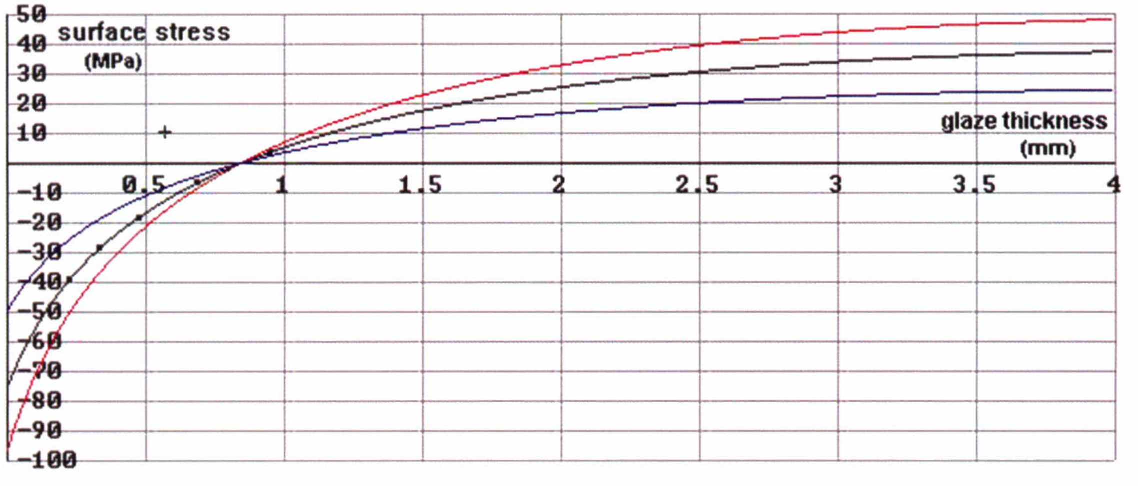
Figure 8. SEM picture of the glazed tile fracture section

3.4. INFLUENCE OF GLAZE THICKNESS ON RESIDUAL STRESS

Considering the Timoshenko equations, Figures 9 and 10 indicate that increasing glaze thickness (in the applicable range) encourages the curvature-induced stress, and hence enhances tensile stress at the interface.

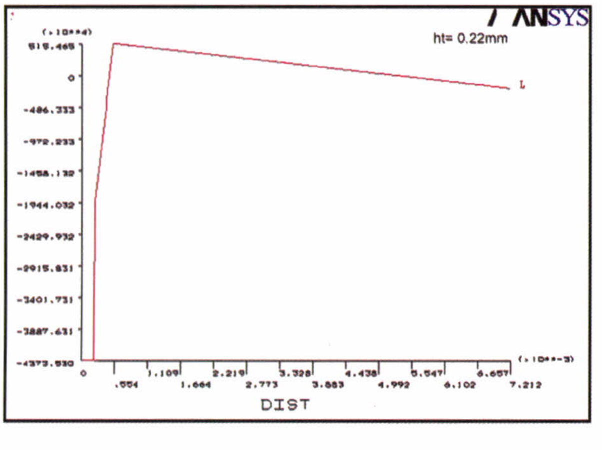
It also decreases the compressive stress in the glaze surface and even makes it change to tensile stress.

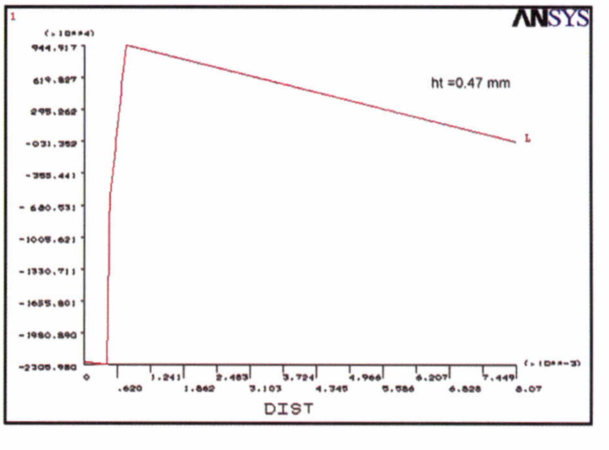




Figures 9, 10. Residual stress at the interface and glaze surface for different glaze thicknesses of tiles for three different applied glazes.

The FEM results shown in Figure 11 and Table 8 confirm the trend.





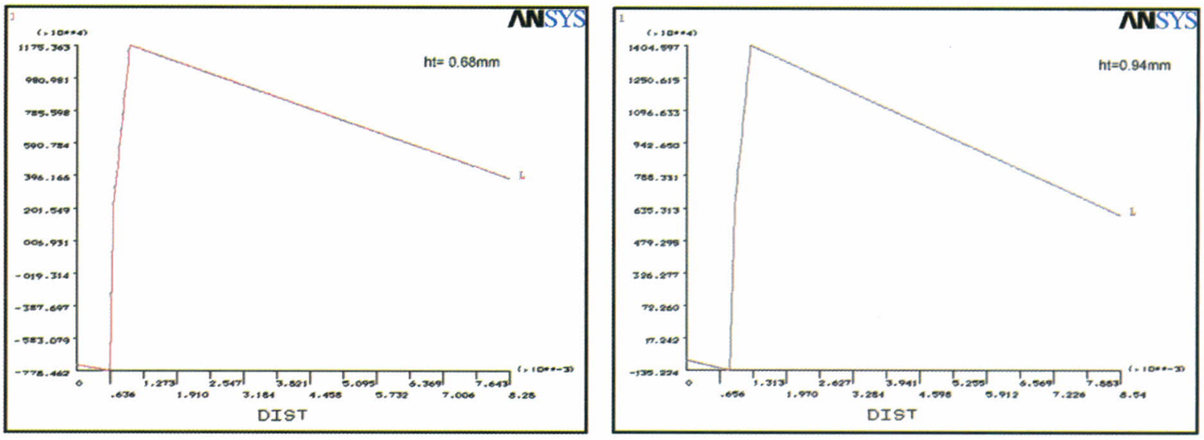


Figure 11. Residual stress profile in tiles with different glaze thicknesses (according to FEM)

Glaze thickness (mm)	Surface stress (GPa)	Interface stress (GPa)
0.22	- 43.75	5.15
0.47	- 22.9	9.44
0.68	-7.78	11.75
0.94	-0.4	14.04

Table 8. Residual stress at the interface and glaze surface in tiles with different glaze thicknesses (FEM results)

Therefore, adequately lowering glaze thickness will result in minimizing dangerous tensile residual stress at the interface and raise the compressive stress of the glaze surface.

3.5. INFLUENCE OF GLAZE TEC ON RESIDUAL STRESS

Increasing the TEC difference between the glaze and body (by lowering the glaze TEC, while glaze thickness is constant) simultaneously raises the body tensile stress at the interface as well as compression in the glaze.

The results are presented in Figures 9 and 10. Table 9 illustrates the same results obtained through applying FEM.

Glaze TEC (0-550)°C $X10^{-6}$ / °C	Interface stress (GPa)	Surface stress (GPa)
(A) 6.91	7.5	-38.3
(B) 6.35	9.1	-45.5
(C) 7.58	5.4	-27.9

Table 9. Residual stress at the interface and glaze surface in tiles with different glaze TECs (FEM results)

3.6. THE IMPORTANCE OF RESIDUAL TENSILE STRESS

Applying an engobe as an interlayer with a higher TEC than those of the glaze and body enables producing a three-layered piece that contains the tensile residual stress concentrated in the engobe layer.

The SEM studies highlight the vital importance of the critical tensile residual stress concentration in the area, since some cracks can be observed in the engobe layer, as shown in Figures 12 and 13.

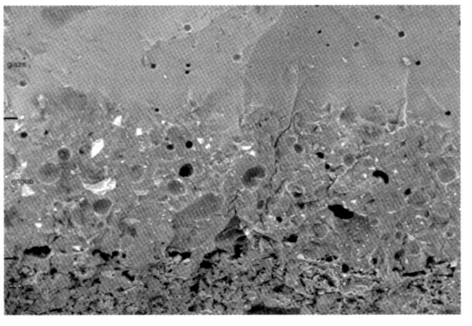


Figure 12. SEM picture of the glazed tile cross section showing cracks in the engobe layer (100 microns)

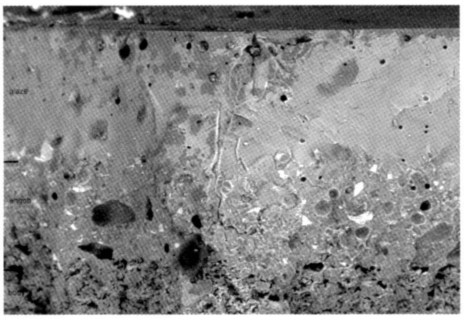


Figure 13. SEM picture of the glazed tile cross section showing cracks in the engobe layer (200 microns)

3.7. CONFIRMING THE AFOREMENTIONED RESULTS BY EXAMINING THE GLAZE CRAZING RESISTANCE

Crazing was not observed even in the specimen with the thickest glaze, when examined according to EN 105.

Subsequently, when repeating the test cycle (according to ASTM 424), SEM observations indicated crazing in the sample with the thickest glaze (containing the most dangerous residual stress profile), as shown in Figure 14. Therefore, once again the critical significance of residual tensile stress was confirmed.

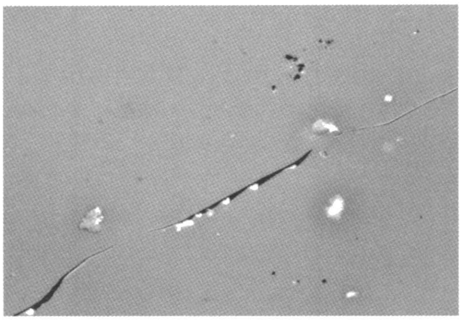


Figure 14. SEM picture related to cracks observed in the glaze surface of tile with thick glaze after the autoclave test.

4. CONCLUSION

The thermal expansion difference between glaze and body, from glaze solidification temperature to the end of the cooling cycle, is the origin of residual stress in glazed ceramic tiles.

The Timoshenko model and also FEM results indicate good agreement with the experimental curvature measurement values. Thus, the validity of these two modelling methods was verified and confirmed for fast double-fired glazed ceramic tiles.

Moreover, considering the elastic behaviour of the usually applied thin glazes, these were used to estimate the residual stress profile in the glazed ceramic tile.

Increase of glaze thickness results in greater values of curvature, increase of interface tensile stress and decrease of surface stress, provided that a glaze with lower thermal expansion than that of the body is applied.

Regarding the influence of glaze thickness on residual stress distribution in a glazed tile, it should be noted that tiles with more curvature sometimes may not contain more compressive residual stress in the glaze.

The greater difference between glaze & body thermal expansion led to simultaneous increase of tensile stress at the interface and compression in the glaze.

When raising the TEC difference between the glaze and body, the destructive effects of tensile residual stress at interface should be also taken into account, besides the required increase of compressive stress in the glaze surface.

The existence of some required compressive residual stress in the glaze, considering the high moisture expansion potential of porous earthenware bodies, while minimizing interface tensile stress, can be achieved through optimizing material properties and process variables.

The importance of the existing tensile residual stress within the interface and its detrimental effect were confirmed through observing cracks in the engobe layer containing tensile stress, and also crack propagation during the autoclave test in specimens with a thick glaze.

In accordance with the advantages of applying thinner glaze and also the benefits of applying an engobe layer, further investigation of the three-layered component can be conducted in order to optimize tile properties, by using the Timoshenko model and FEM analysis.

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