CERAMIC TILE MECHANICAL BEHAVIOUR ON IMPACT

G. Silva, A. Muñoz, C. Felíu, V. Cantavella

Instituto de Tecnología Cerámica (ITC)
Asociación de Investigación de las Industrias Cerámicas
Universitat Jaume I. Castellón. Spain.

ABSTRACT

Impact resistance is one of the most critical characteristics to be taken into account in assuring the suitability of ceramic products for use in severe service conditions. The test methods currently available for evaluating ceramic tile behaviour under these conditions are inappropriate, as they depend on systems of subjective visual appraisal, or are based on determining physical parameters of the material unrelated to the observed surface defects. An instrumental measurement system has been developed, capable of quantifying the mechanical alterations that arise on impingement by rigid objects, even when visible damage does not appear at the surface. The assembly consists of an impactor fitted with a force measurement sensor on a pendulum system, which enables evaluating material behaviour at different impact velocities. The system is highly versatile, and can reproduce different conditions of use, allowing adjustment of the test variables (total impactor mass and impinging tip geometry) to specific needs.

To evaluate the level of damage produced under certain impact conditions, a quantitative parameter has been defined relating to the mechanical response of the surface at the initial moments of impact. A mathematical model has been used to theoretically analyse the impact of spherical bodies on rigid flat surfaces; the theoretical results match those found on using the test assembly. The defined parameter is related to the elastic constants of the material (Young's modulus and Poisson ratio) and enables evaluating the arising changes in the elastic behaviour of the surface, produced by the formation of microcracks on impact. A study was carried out with different types of ceramic materials to verify the repeatability of the method and the effect of impact conditions (energy developed, velocity, geometry of the impinging object, etc.). The results obtained confirm the suitability of the new test system for quantitatively assessing ceramic tile impact resistance. Using the developed test method, assessment has been initiated of the effect of different product parameters (type of glaze, thickness of the layers, effect of the base, etc.) on tile impact resistance, with a view to defining materials design criteria for improving the mechanical behaviour of these products.

1. INTRODUCTION

On using the term "ceramic", despite the wide range of materials covered, there may be an underlying association with the concept of fragility, either due to traditional ceramic uses in making artware or to its relationship with household cookware. Moreover, the problems associated with fractures, formerly appearing in certain ceramic floor and wall tilings, which in most cases stemmed from inadequate installation, have created an erroneous image of inappropriate performance on impact.

For some reason or another, impact resistance has been a little used characteristic for evaluating the behaviour of ceramic materials. Until a few years ago test methods were not even available for this purpose. At present, the advances in ceramic tile installation systems, driven by the improvement in fixing materials and better training of tile fixers, have practically eliminated the risk of tile failure, limiting possible pathologies to surface deterioration phenomena.

However, the test methods described in the literature [1, 2, 3], based mainly on systems of free falling metal spheres of various sizes, are inappropriate for evaluating the surface damage caused by impact on ceramic tiles for one or more of the following reasons:

- The test to determine the energy required to produce tile failure is performed on specimens not installed on a rigid base, under very different conditions from those that the product will face in actual use.
- Visual appraisal criteria are used to assess the damage caused, which fail to ensure appropriate reproducibility or enable quantifying the results obtained.
- Test methods are based on determining physical parameters associated with the elastic characteristics of the material, unrelated to the arising surface damage (chips and cracks).

The need to quantify the damage produced during impact, in order to define the resistance of the materials as well as to evaluate the contribution of product design variables, has led to using different quantitative instrumental techniques, such as indentation, accelerometry[4] or ultrasonics measurements in different studies on the mechanical behaviour of materials. Although these techniques allow evaluating the changes that the material undergoes during the application of force, in the present study a prototype has been used, designed to evaluate the mechanical response of the surface simultaneously with the impact phenomenon, incorporating a dynamic force sensor in the actual impinging element.

The assembly is made up of an adjustable platform that bears a pendulum system (Figure 1), consisting of a carbon fibre mobile bar and an impactor fitted with a piezoelectric force measurement sensor. The electric signal generated, linearly proportional to the force acting on the sensor, is recorded in a high-frequency oscilloscope to determine the evolution of stress and arising strains during impact.

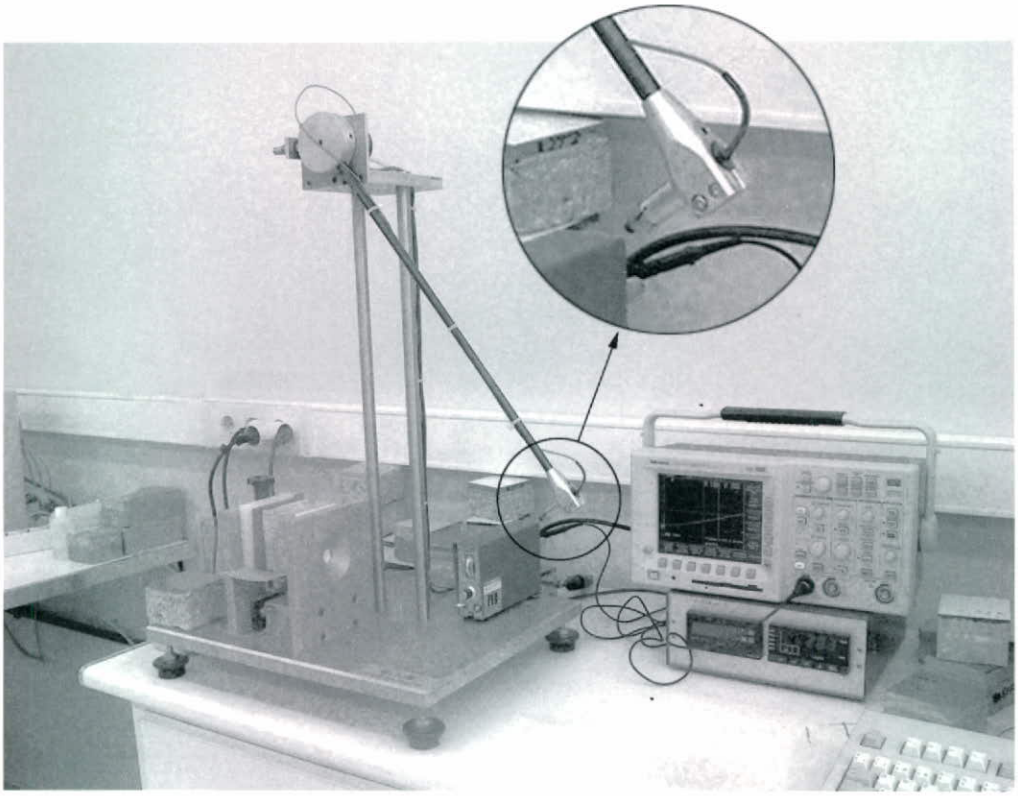


Figure 1. General view of the prototype.

The prototype is equipped with a sensor set at an angle on the swivelling axis of the mobile arm, which allows establishing the initial height of the impactor as well as linear velocity at the moment of impact, and hence energy input. The use of a pendulum system enables carrying out impact tests with energy levels close to crack generation initiation at the surface, as well as conducting successive repetitions at the same surface point. The assembly is highly versatile and can reproduce different conditions of use on modifying impinging object mass and impactor tip geometry.

To reproduce the phenomenon under similar conditions to those found in service, test specimens are fixed by a rigid resin layer on blocks of reinforced concrete measuring 7.5x7.5x5 cm, following the procedure set out in standard UNE-EN ISO 10545 Part 5. A pneumatic fastening system ensures the perpendicular alignment of the surface of the material to the sensor-fitted impactor.

2. MECHANICAL BEHAVIOUR DURING IMPACT

When two objects collide, the force applied to the surface produces a strain that can be reversible (elastic behaviour) or permanent (plastic behaviour) depending on the characteristics of the material [5,6]. Many materials, such as metals, present both types of behaviour, depending on the intensity of the applied force. For small values of applied force, an elastic strain is produced proportional to Young's modulus (E), but on exceeding a certain limit value, the resulting strain ceases to be reversible and loses its linear growth relation to applied force. If stress continuous to rise, the strain progressively stabilises until reaching a maximum value at which fracture occurs.

Homogeneous ceramic materials, and glasses in general, are characterised by exhibiting a rapid transition from elastic behaviour to fracture, due to their low mechanical stress relaxation rate on not presenting appreciable plastic strain to enable absorbing these stresses. These materials are known as fragile materials, in contrast to ductile materials, in which fracture is preceded by plastic strain.

For the typical energy levels associated with falling household objects, under appropriate installation conditions that impede energy absorption by tile bending, the arising strains and damage are limited to the surface of the material without producing failure of the ceramic body. From the moment of initial contact, the stress withstood by the surface grows parallel to the arising strain until peaking, which corresponds to the moment of maximum surface strain (Figure 2).

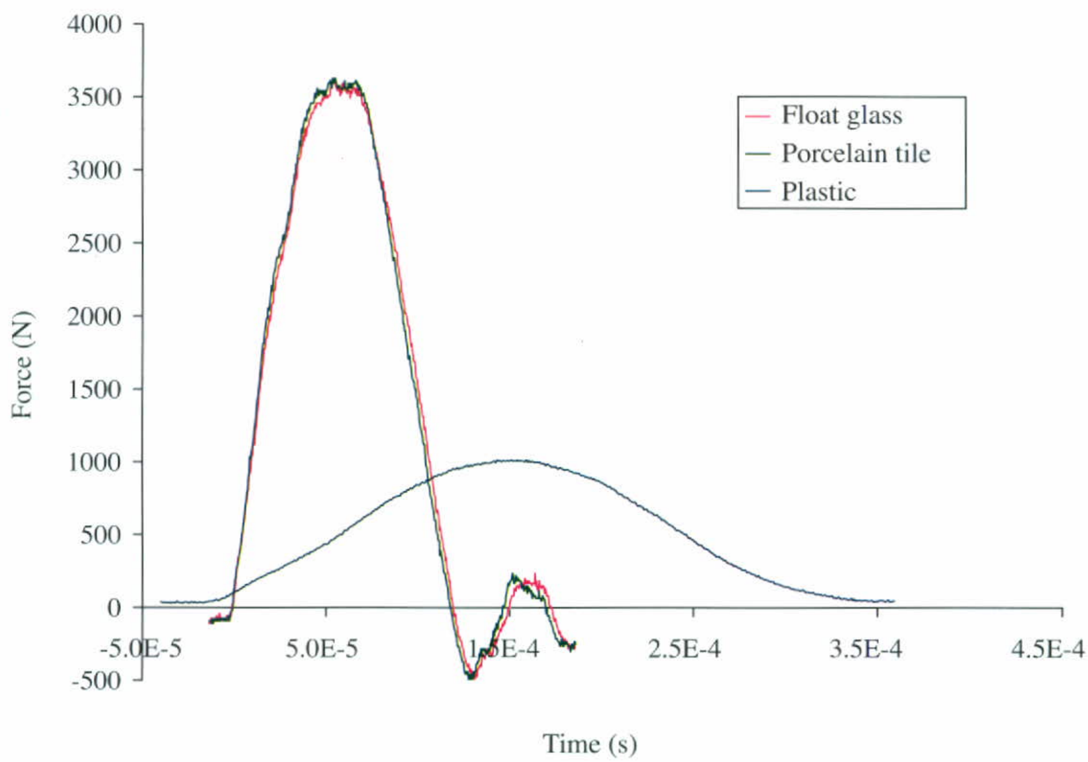


Figure 2. Evolution of force with time for different materials.

After reaching the maximum force value, the impactor inverts its trajectory and the material begins to recover its initial form, with progressive reduction of the applied stress until contact between impactor and material ends. In the case of rigid materials, such as glass and ceramic tiles, high maximum force values are found. Furthermore, contact time between the surface and impinging object is short, this value being proportional to the system's elastic constants. On the other hand, materials with a greater capacity to deform have longer contact times and they withstand lower forces, as in the case of plastic.

Similarly, on increasing the velocity of the impinging object at the moment of impact, which rises proportionally to the square root of fall height, the maximum force value attained increases proportionally, while contact time remains approximately steady (Figure 3).

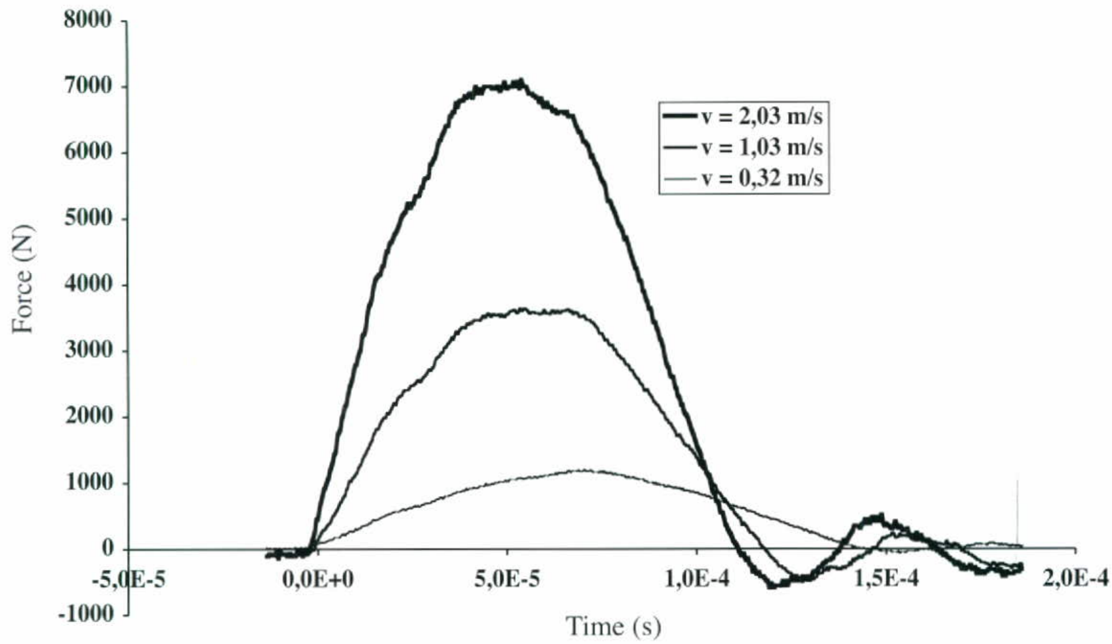


Figure 3. Evolution of force during impact from different heights.

Furthermore, the evolution of force exhibits an approximately sinusoidal behaviour, similar to the behaviour that would be found during impact of a sphere of reduced mass on the flat surface of a theoretical material with pure elastic behaviour [7]. On a macroscopic level, this implies that the response of the tile-adhesive-base system can be analysed, assuming an elastic behaviour and characterising it by means of a parameter (e.g. the coefficient of restitution) related to its absorbing capacity.

However, significant differences are not found in the shape of the curves F=f(t) corresponding to different impact velocities; at low values no surface damage occurs, while at high velocities concentric and/or radial cracks are produced, and even surface chipping. It is therefore necessary to assume that these fractures do not produce a sufficiently substantial variation to be detected in the evolution of the force withstood by the surface, or they are generated and/or propagated after contact time with the impinging object, during the surface stress relaxation phase.

3. THEORETICAL ANALYSIS OF RESPONSE DURING IMPACT

The instantaneous force developed during impact of a spherical object on a flat surface of much greater mass can be found on applying the laws of elastic contact from:

$$F = k \cdot x^q \qquad [1]$$

where k is a constant that depends on the mechanical and geometric properties of the materials that collide and q an exponent that takes the value 1.5 if a hertzian type contact is assumed[7]. Developing the differential equation of motion, applying a series of simplifications and approximations, an expression is derived that defines force versus time:

$$F(t) = m_1 \frac{1.14V_0^2}{\alpha_m} sin\left(\frac{1.68V_0 t}{\alpha_m}\right) \qquad [2]$$

where m_1 is mass of the spherical object, V_0 velocity at the initial moment of impact, and α_m the maximum strain reached, which in turn can be expressed in the form:

$$\alpha_m = \left[1.25\frac{m_1 V_0^2}{k_2}\right]^{\frac{1}{2.5}} \qquad [3]$$

where k_2 is a constant proportional to the square root of the radius of the spherical object (R), and depends on the Young's modulus and Poisson ratio of both objects, as follows:

$$k_2 = \frac{4}{3}\sqrt{R}\left[\frac{1}{\frac{1-\nu_1^2}{E_1} + \frac{1-\nu^2}{E}}\right] \qquad [4]$$

The evolution of force has been confirmed to follow an approximately sinusoidal behaviour versus time, as predicted by the theoretical equations. However, the response of the material can only be considered fully elastic in the initial moments of impact, while the characteristic critical stress/strain values of each material are not exceeded. For this reason it was decided to use the value of the initial maximum slope of force growth versus time as a reference. Equation 2 enables deriving the following expression:

$$\left.\frac{\partial F}{\partial t}\right|_0 = C_1 \cdot V_0^{1.4} \qquad [5]$$

$$C_1 = f(k_2^{0.8}, m_1^{-0.2}) \qquad [6]$$

Based on the results of the impact tests conducted on a range of glazed and unglazed ceramic materials, it was confirmed that these materials exhibit this relation of potential growth versus velocity, it being possible to characterise their elastic response on the basis of this parameter. As Figure 4 shows, the potential adjustments for all the types of materials exhibit correlation coefficients very close to unity, with exponents around 1.4, as equation 5 predicts.

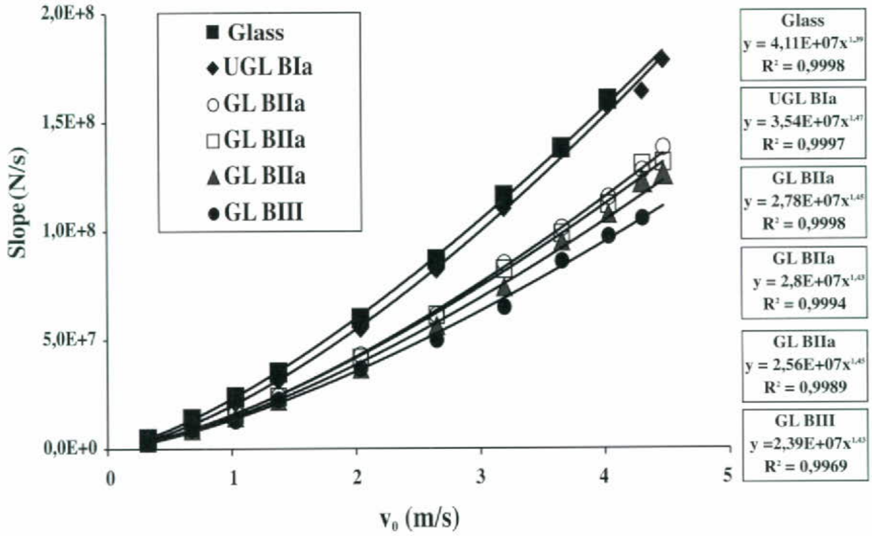


Figure 4. Evolution of the initial slope versus velocity for different materials.

4. TYPES OF FRACTURE

Fracture mechanisms in ceramic materials have been widely studied since the first investigations on conical fractures in lenses (Hertz, 1880) until the present time. Two types can basically be distinguished: the fragile mode, also called hertzian fractures, and the pseudo-plastic mode[8].

When a spherical object exercises a growing force on the flat surface of a rigid, homogeneous material, it produces a strain in the surface with rising tensile stress in the contact area between both elements, reaching maximum stress levels in the circular line that delimits this area. When a critical load value is reached, a ring crack initiates at the surface of the material, coinciding with the line where the tensile stresses are concentrated, which can propagate inwards forming a conical-shaped fracture.

It has been experimentally observed that the load needed to start this has a linear relation to the radius of the impinging sphere (Auerbach, 1891), with an increasing depth being reached on raising the load applied to the surface. This behaviour, widely studied by means of static and dynamic load tests with spherical indenters, is similarly found in impact phenomena on homogeneous materials. Figure 5 shows the development of a conical crack in the cross section of a porcelain tile test specimen, after impact with a spherical tip of approximately 3 mm radius.

Figure 5. Hertzian fracture in a porcelain tile.

Figure 6. Pseudo-plastic fracture in a stoneware body.

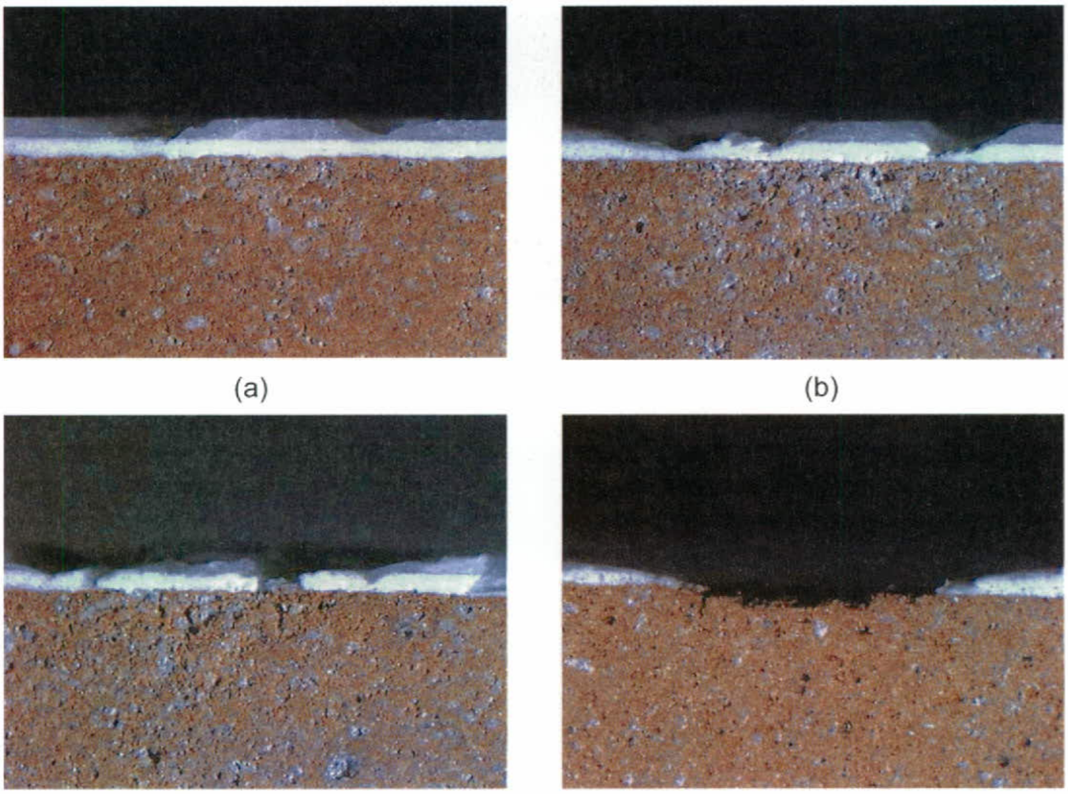
On the other hand, heterogeneous ceramic materials, with defined interfaces and high grain size exhibit quite different behaviour, not presenting any tendency to hertzian fracture. Under similar load application conditions, an area of strain is generated subject to intense shear stresses under the surface in contact with the sphere, while maximum shear stress concentrates along the contact axis at a depth approximately half the contact radius. This strain, apparently similar to the one characterising plastic strain processes in metals, consists of multiple short microcracks, generated by the shear stresses and scattered in the strain area, which has an approximately semicircular form (Figure 6). On applying higher loads, tensile stresses can arise that spread secondary cracks starting from the initial damage.

This type of fracture, called pseudo-plastic, appears at a macroscopic level in a similar way to plastic strain phenomena, with slight sinking of the surface after impact. However, advancing damage under the contact surface can lead to the coalescence of microcracks produced by shear, capable of generating cracks under the surface and even material detachment.

These two fracture mechanisms represent the extreme cases corresponding respectively to highly homogeneous and heterogeneous materials. In practice, the main fracture mechanism exhibited by a certain material will depend on its nature and on its internal microstructure, while there can also be a progressive transition between both models [9].

Analysis of the evolution of impact damage becomes much more complicated in the case of multilayer systems, currently a growing research field. In the specific case of a type of glazed ceramic tile, made up of a system of three layers of different nature and behaviour (fully heterogeneous ceramic body, relatively homogeneous glaze and engobe), a transition is observed between both fracture mechanisms, which can even coexist depending on the intensity of the force applied and curvature radius of the impinging object.

The picture sequence shows that at small fall heights (a) the main fracture mechanism is of a hertzian type, exclusively affecting the homogeneous glaze layer, although the beginning of a pseudo-plastic strain below the contact area with the



(a) (b) (c) (d)

Figure 7. Evolution of impact damage in a multilayer system.

impactor starts to appear. On raising the fall height, and therefore velocity at the moment of impact, the hertzian fracture advances, also affecting the engobe layer and subsurface strain increases (b). At a higher level of impact energy, besides detachments of the glaze coating, small cracks and holes appear under the impact area (c), due to the coalescence of microcracks generated by interparticle slippage. Finally, advance of these fractures can give rise to cracks in the ceramic body and detachment of part of the material (d).

This behaviour can vary significantly depending on the nature, homogeneity, thickness and distribution of the layers that build up the surface, opening up a wide range of possibilities which need to be assessed in order to improve the mechanical behaviour of ceramic materials.

5. METHOD FOR QUANTITATIVE FRACTURE EVALUATION

As indicated previously, the curves of the evolution of force versus time F=f(t) do not exhibit any significant change associated with the generation of surface fractures. Due to the difficulty of evaluating the arising damage simultaneously with the unfolding impact process, it was decided to determine the alterations arising during collision by evaluating the changes in the elastic response of the material, by means of a second impact of equal energy at the same point.

Out of the various parameters described in the literature for characterising the elastic response of the surface (maximum strain, contact time, etc.), the maximum slope of force growth at the initial moments was chosen as a reference, because it presents the greatest sensitivity for detecting changes in microstructure caused by impact. When alterations do not occur at the surface of the test specimen, the value of the initial maximum slope in both impacts should be identical, confirming the absence of surface damage. Starting at a critical velocity value, which depends on the type of material, fractures begin to occur in the surface, revealed by a decrease in the initial slope of the second impact (Figure 8), with a progressive increase in difference between both slopes proportional to the arising level of damage, on raising the object's fall height.

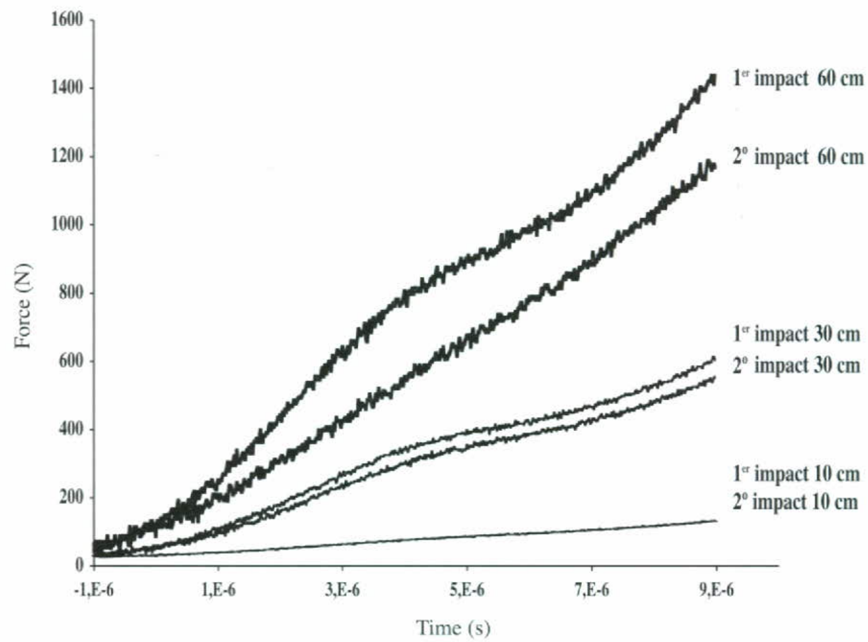


Figure 8. Evolution of force at the initial moments.

To quantify the level of damage generated during the first impact, the standard difference is used, defined as the variation between the slopes found in both impacts, calculated by linear regression of 100 pairs of individual values (equivalent to 2μs), and divided by constant C_1 of the potential adjustment, which depends on the elastic parameters of the material, in order to allow comparing the absolute values found between different materials and geometries of the object, from:

$$Standard\,.\,difference = \frac{\left.\frac{\partial F}{\partial t}\right|_{impact\,1} - \left.\frac{\partial F}{\partial t}\right|_{impact\,2}}{C_1} \qquad [7]$$

Figure 9 plots the evolution of the maximum slopes of both impacts and of the standard parameter, in the tests carried out on a glazed stoneware tile. At low initial velocities below 1 m/s no surface damage or significant differences between the values of the slopes found in both impacts are observed, so that alterations can be assumed not to exist in the material.

When progressively increasing impactor fall height, i.e., initial velocity at impact, a progressive rise in difference is found between the initial slopes, which increases proportionally with the level of observed damage.

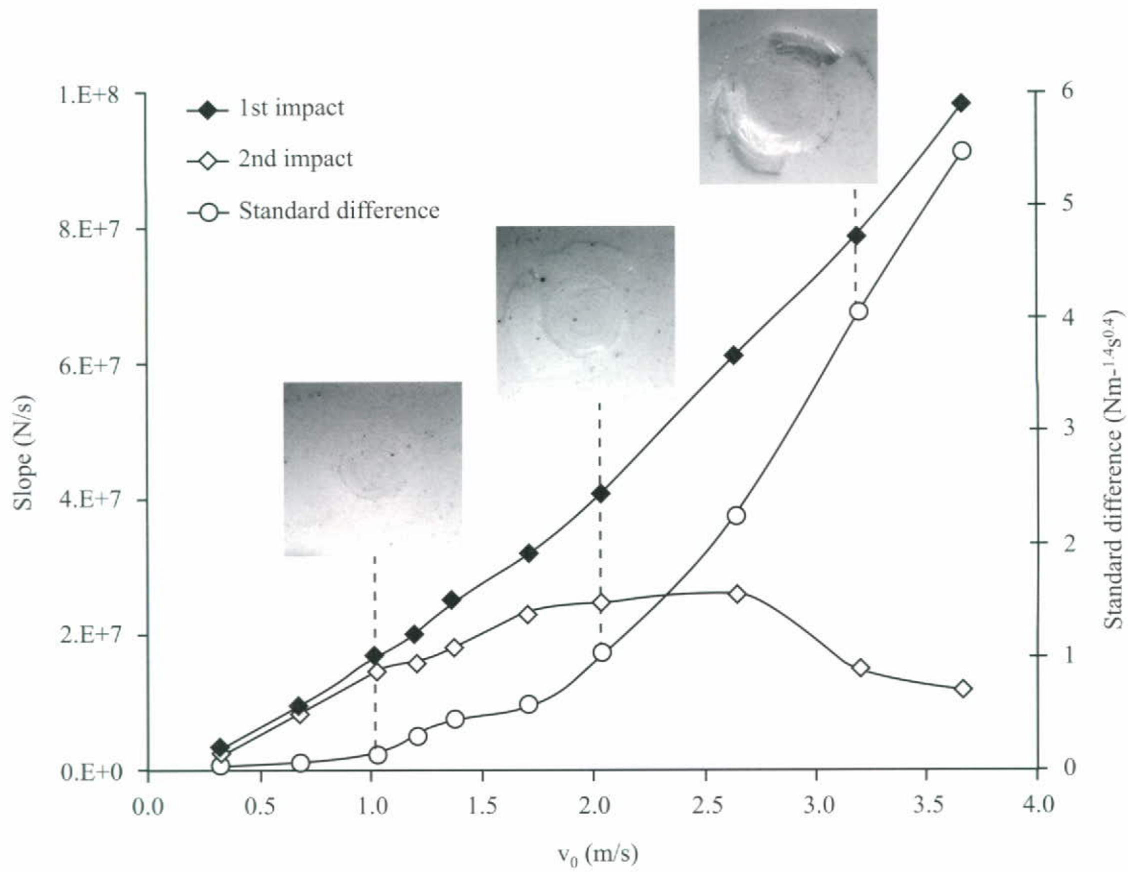


Figure 9. Evolution of the standard parameter versus impact velocity.

At velocities higher than 3 m/s an abrupt change is observed in the slope of the second impact, coinciding with the appearance of chipping in the glazed surface. Analysis of the absolute difference curve enables determining the minimum energy at which defects are generated in the surface, as well as their evolution on raising impact energy.

6. EFFECT OF OBJECT CHARACTERISTICS ON RESPONSE DURING IMPACT

A) OBJECT TOTAL MASS

When an object impinges on a test specimen not fixed on a rigid base, this deforms by bending until the strain limit is reached and a crack initiates at its rear side, which advances till causing failure of the material. Under these conditions, the energy required to fracture the piece, which depends on the characteristics of the material and its thickness, presents an approximately constant value, while the height needed to cause fracture increases proportionally on reducing object mass.

On the other hand, under appropriate installation conditions, most of the kinetic energy transmitted during collision is recovered indirectly in the object rebound process, while the energy put into the generation and propagation of surface damage is significantly reduced with regard to total energy developed. For this reason, raising impinging object total mass produces no advance in damage proportional to the corresponding rise in energy.

To verify the influence of object mass on arising surface damage, tests were carried out incorporating an additional mass at the back of the impactor, until approximately doubling its initial value. Figure 10 plots the results found with both masses.

It shows that the initial slope of force growth does not present a significant dependence on object mass, as predicted by equation 6. This implies that the evolution of force during the initial moments is equivalent and depends mainly on the elastic characteristics of the surface-object system.

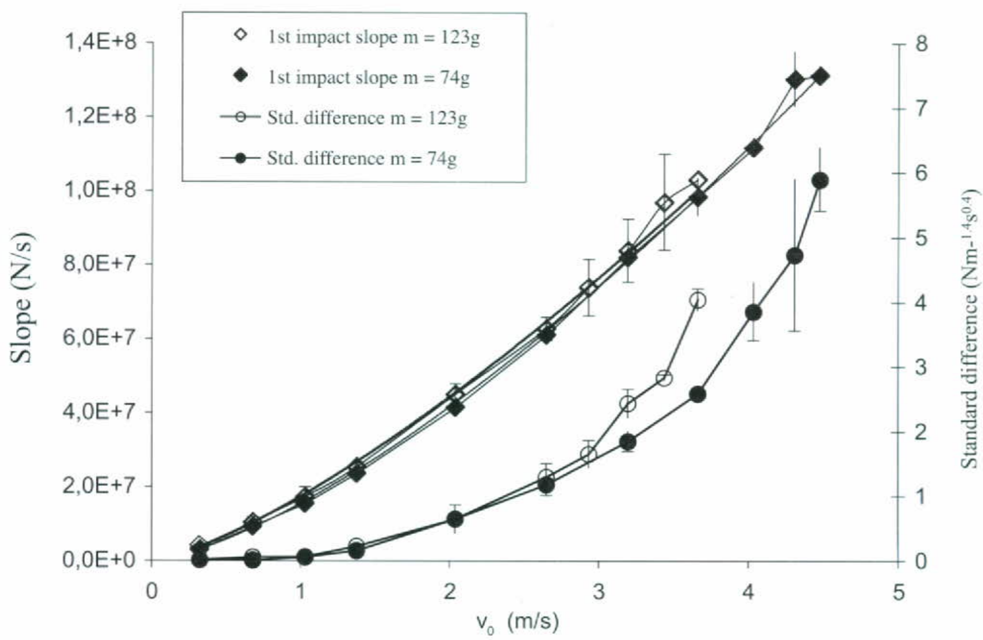


Figure 10. Influence of mass on material response.

The increase of object mass, holding contact geometry, slightly raises the value of force and maximum strain reached, and therefore increases contact time between both objects. However, this increase in mass only translates into a small increase in impact damage, the effect of a rise in object mass being much less critical than the increase of its fall height.

B) OBJECT CONTACT GEOMETRY

With a view to determining the effect of object geometry on arising damage, a series of tests was carried out with spherical tips with a different curvature radius (R). Figure 11 plots the full set of data obtained in the impact tests conducted at the same velocity on polished porcelain tile test specimens with different tips. On increasing impact tip curvature radius, a rise in the maximum force value is observed, as well as a reduction in contact time between the object and the surface. This indicates that the response of the system becomes more rigid on increasing contact curvature radius, so that the system's elastic constant would be expected to rise.

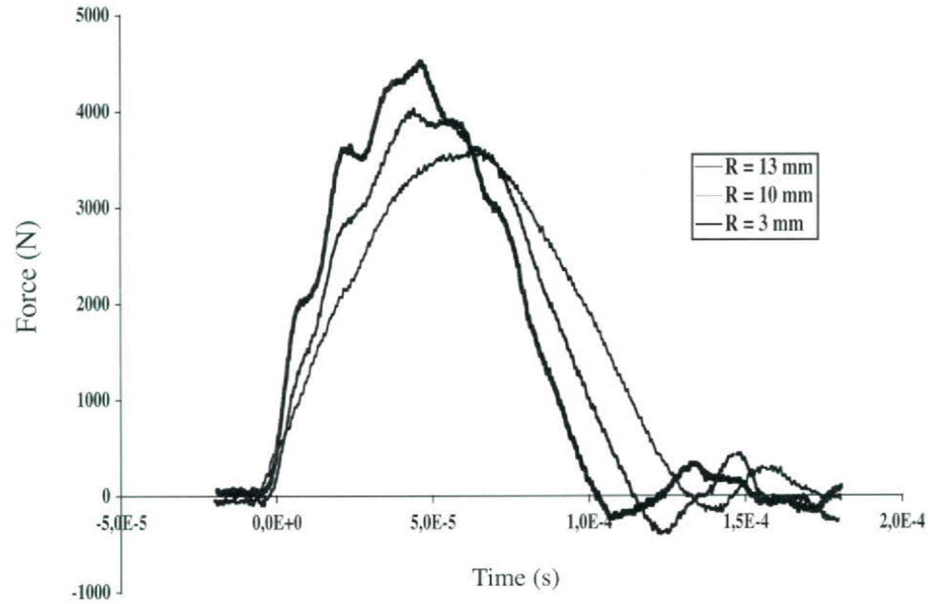


Figure 11. Influence of impact tip geometry.

In fact, if we analyse the evolution of the initial slope values versus velocity for each type of impact tip (Figure 12), it is found that the slope of the potential adjustment (C_1) increases progressively on raising the value of R. As predicted in equation 4, the value of the system's elastic constant (k_2), increases proportionally to the square root of object curvature radius, so that the maximum strain generated on impact by objects of larger radius decreases.

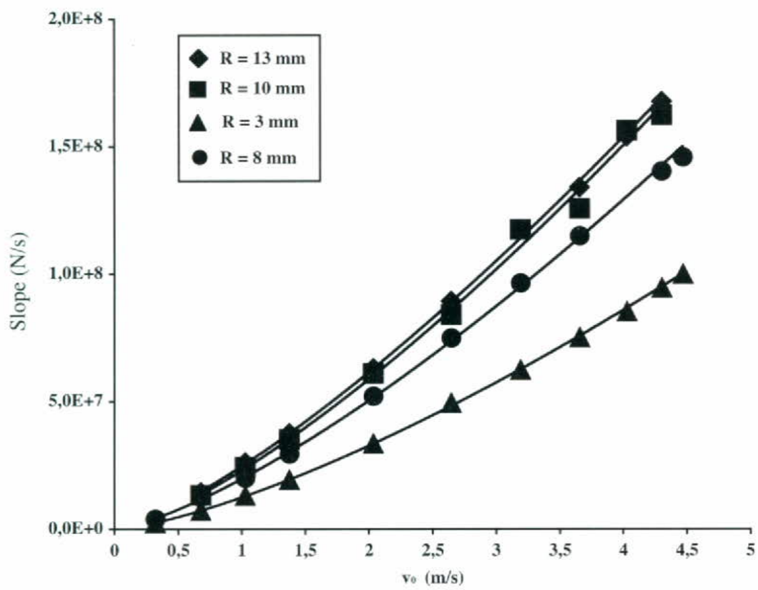


Figure 12.Evolution of the initial slope versus object curvature radius.

This interdependence between system elastic parameters and object curvature radius could be used to evaluate materials elastic constants, by carrying out tests with tips of different geometry and analysing the growth of constant C_1 from the initial slope adjustment.

Analysis of the damage generated using different impact tips confirms that increasing object tip curvature radius significantly lowers arising surface damage. As indicated previously, increasing the contact surface decreases the maximum penetration attained (α_m), so that surface stresses will be smaller and the tendency to produce hertzian fracture will decrease.

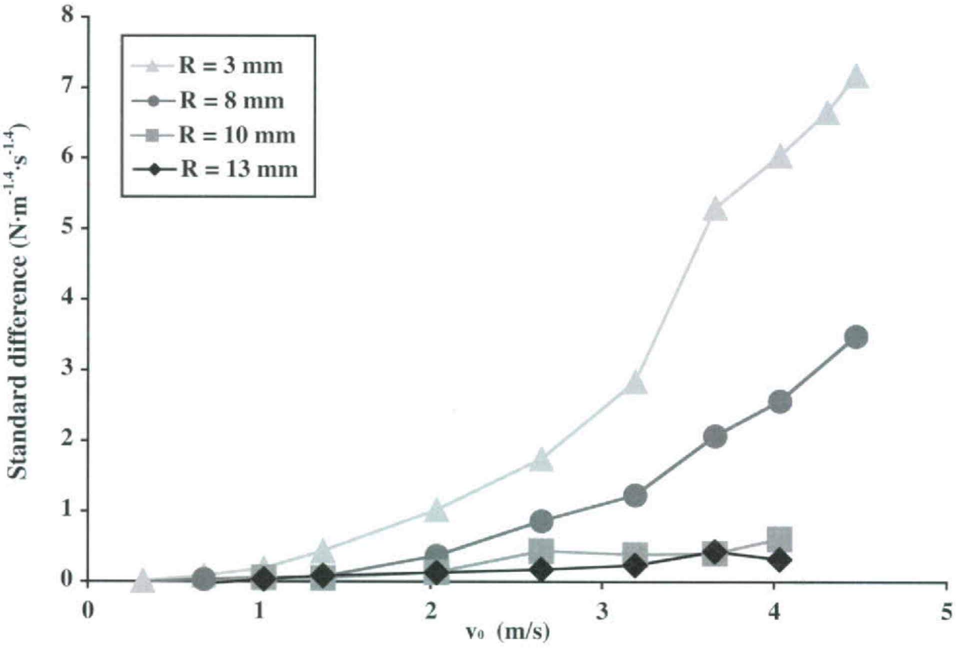


Figure 13. Evolution of the damage generated with different geometries.

As Figure 13 shows, on raising the curvature radius a higher velocity is required to cause hertzian fractures to appear in the material. The arising concentric cracks present a larger diameter on increasing tip radius, because tensile stresses concentrate on the contact area perimeter. Moreover, the advance of the arising damage flattens on increasing object radius, with only concentric cracks appearing at the surface with high values of R.

This means that contact geometry, together with fall height, are the most critical factors affecting the evolution of surface damage. It will therefore be necessary to accurately define test conditions to evaluate materials impact resistance.

7. CONCLUSIONS

The following conclusions can be drawn from the study:

- An instrumental assembly has been developed that allows analysing the mechanical behaviour of materials by means of a quantitative evaluation of the changes that occur in the elastic response of the surface on impact by spherical objects. The proposed method has high repeatability and enables reproducing different real conditions of use, by modifying test parameters (impinging object mass, contact geometry and impact velocity).

- Surface response during the initial moments of impact can be analysed, on assuming pure elastic behaviour, which enables using the proposed method to evaluate characteristic elastic parameters of the materials.

- The types of fracture that different types of ceramic materials exhibit have been analysed. In the case of glazed ceramic tiles, hertzian and pseudo-plastic fracture mechanisms can coexist simultaneously, so that behaviour on impact can vary significantly depending on the nature and distribution of the constituent layers.

- The effect of test conditions on response to impact has been studied. It was confirmed that the geometry of the impinging object and velocity at the moment of contact are the variables that most alter the appearance and advance of surface damage.

- The method developed allows studying product design variables (composition, microstructure, layer thickness and distribution, etc.) and installation conditions (rigidity of the base, type of adhesive, etc.) with a view to improving the mechanical behaviour of ceramic floor and wall tiles.

8. REFERENCES

[1] BS 1281:1974 Specification for glazed ceramic tiles and tile fittings for internal walls. Appendix 2. (Cancelled)

[2] Revêtements de sol céramiques - Spécifications techniques pour le classement UPEC- Annexes 7 et 8 (Cahier du CSTB 3243, livraison 411 de Juillet-août 2000)

[3] ISO 10545-5: 1996 Ceramic tiles. Part 5: Determination of impact resistance by measurement of coefficient of restitution.

[4] MARCO, J. et al. Application of accelerometry to measurement of mechanical properties of materials. In: *Qualicer 98*. Castellón: Cámara Oficial de Comercio, Industria y Navegación, 1998.

[5] CALLISTER, W.D. (ed.). Introducción a la Ciencia e Ingeniería de los Materiales. Barcelona: Reverté, 1995-1996.

[6] HIBBELER, R.C. Mechanics of materials (2nd. ed.). New York: Macmillan College, 1994.

[7] MARUR, P.R.; TIPPUR, H.V. Evaluation of mechanical properties of functionally graded materials. *J. Test. Eval. (JTEVA)*, 26 (6), 539-545, 1998.

[8] LAWN, BRIAN R. Indentation of ceramics with spheres: a century after Hertz. *J. Am. Ceram. Soc.*, 81(8), 1977-1994, 1998.

[9] GUIBERTEAU, F.; PADTURE, N.P.; LAWN, B.R. Effect of grain size on hertzian contact in alumina. *J. Am. Ceram. Soc.*, 77(7), 1825-31, 1994.