Chapter 12

Investigation of Mechanical Behaviour of a Bioceramic

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Additional information is available at the end of the chapter

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Abstract

In order to find a convincing method to measure bioceramics fracture toughness, tensile strength and modulus, a novel configuration of the Brazilian test was applied and described in the experimental work. The flattened Brazilian specimens, which are in the shape of discs having parallel flat ends, are subjected to compression for determination of opening mode I fracture toughness K_{IC}. Experiments were done by using tricalcium phosphate-fluorapatite composites, which were tested by compressive loading on the parallel flat ends. The loading angle corresponding to the flat end width is about 2α = 20° in order to guarantee crack initiation at the centre of the specimen according to the Griffith criteria. Fracture toughness was also performed by using semi-circular bend "SCB". Finite-element program, called ABAQUS, is used for numerical modelling for finding stress intensity factors. The effects of fluorapatite additives and fracture toughness were studied. Fracture toughness values of tricalcium phosphate-fluorapatite composites were found to increase with increasing addition of fluorapatite until an appropriate value. It is shown that there is a good agreement among the experimental, analytical and numerical results.

Keywords: composite, toughness, mechanical properties, flattened Brazilian test, semi-circular bend, numerical modelling

1. Introduction

The development of the ceramic material industry poses the necessity for determining the stress intensity factor (SIF) of bioceramic cracking. Researchers are still studying to find a simple and accurate standard method to determine fracture toughness, which is an important parameter to determine the stress required to drive a pre-existing crack which generally exists in materials. However, the International Society for Rock Mechanics (ISRM) has suggested some methods to determine fracture toughness, listed in Ref. [1]; examples include (1) Chevron

Bend (CB) specimens, (2) Short Rod (SR) specimens and (3) Cracked Chevron Notched Brazilian Disc (CCNBD).

Some methods were previously used to find mode I fracture toughness, K_{IC}, such as Modified Ring (MR) test [2, 3], Diametral Compression Method (DCM) [4], Semi-circular Core in three-point Bending (SCB) [5] and finally Brazilian Disc Test (BDT) [6, 7].

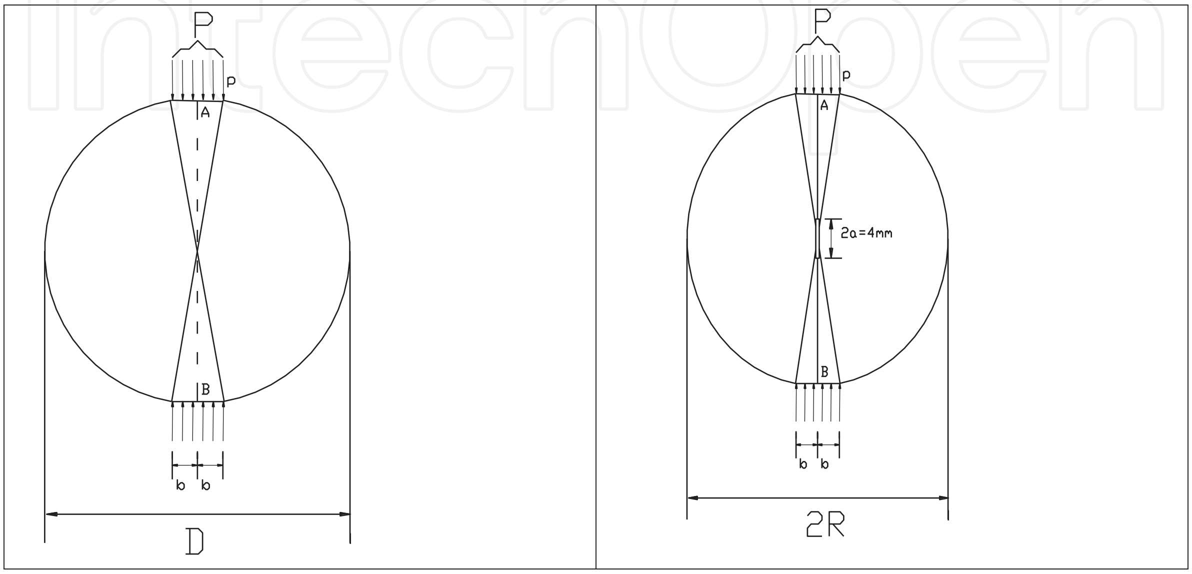

Figure 1. (a) Flattened Brazilian specimen and (b) flattened Brazilian specimen with a central straight-through crack (CSTFBD).

In order to define the mode I elastic modulus, tensile strength and fracture toughness of biomaterials, the central straight through flattened Brazilian disc "CSTFBD" test is ideal for specimens for pure mode I fracture and the well-known test configurations for determining the parameters previously mentioned in just one test. The disc specimen (**Figure 1**) is designed by introducing two equal-width parallel planes in the sample, which are prepared specifically for load application. The loading angle conforming to the flat end width 2α must be greater than a critical value ($2\alpha \geq 20°$) in order to guarantee crack initiation at the centre of the disc [8]. The obtained numerical results are compared with experimental and analytical ones.

Semi-circular bend (SCB) specimens presented in **Figure 2** were used to investigate experimentally the mode I fracture toughness K_{IC} . The SCB specimen was prepared by introducing a straight crack in the semi-disc, which is prepared specifically for measuring K_{IC}.

In this study, we used the commercial tricalcium phosphate (β-CTCP) reinforced with the fluorapatite (Fap) with different amounts of additives (13.26, 19.9 26.52, 33.16 and 40%) sintered at 1300°C. The objective is to determine the stress intensity factors for modified Brazilian test and SCB specimen with analytical formula and numerical simulation. A range of specimen geometries having various crack lengths (a) were modelled and analysed with ABAQUS finite-element program. Fracture toughness values with varying geometric parameters were

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analysed. The mode I crack growth behaviour of Fap-β-CTCP sample is investigated experimentally and theoretically using both CSTFBD and SCB specimens.

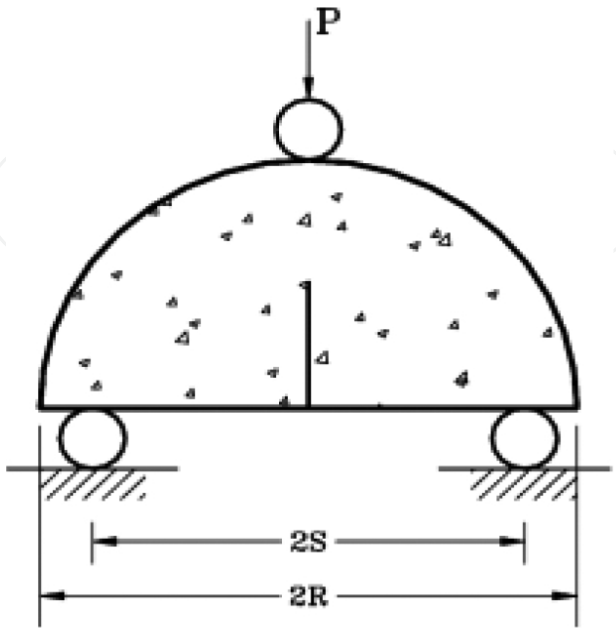


Figure 2. Semi-circular bend specimen (SCB).

2. Materials and methods

In order to elaborate CTCP-Fap, the materials used are the commercial tricalcium phosphate (Fluka) and synthesized fluorapatite. The Fap powder was synthesized by the precipitation method [9]. The approximate representatives Fap-β-CTCP were, respectively [(13.26 wt%, 86.74 wt%), (19.9 wt%, 80.1 wt%), (26.52 wt%, 73.48 wt%), (33.16 wt%, 66.84 wt%) and (40 wt %, 60 wt%)]. Estimated quantities of each powder were milled with absolute ethanol and treated by ultrasound machine for 20 min. The milled powder was dried in a low temperature oven at 80°C to eliminate the ethanol and generate a finely divided powder. Powder mixtures were molded in a metal mould and uniaxially pressed at 67 MPa to form cylindrical compacts with a diameter of 30 mm and a thickness of about 5 mm. The green compacts were sintered in a horizontal resistance furnace (Pyrox 2408) at 1300°C for 1 h 30 min. The heating and cooling rates were 10 and 20°C min^{-1}, respectively.

In this study, we used three different geometries for sample construction: The basic dimensions of the FBD, CSTFBD and SCB specimens were considered to be the same and were as follows:

D = 30 mm and B = 5 mm, with D is the diameter and t is the thickness.

While the SCB and CSTFBD specimens were being added a crack of 4 mm. A LLOYD model test machine is used for the Brazilian and bending tests for the measurement of the fracture toughness, elastic modulus and tensile strength.

3. Determination of mechanical properties of the ceramics specimen using modified Brazilian tests

The mechanical properties of the compacts were measured by Brazilian test. The maximal rupture strength σ_r is given by the following equation [10, 11]:

$$\sigma_r = \frac{2P}{\pi Dt}. \tag{1}$$

where P is the tensile strength, and D. and t are the diameter and the thickness of the sample, respectively.

Yet, in the flattened Brazilian disc, the previous formula is no longer valid. After choosing an appropriate value of 2α, the rupture strength σ_r can be determined by the following equation [8]:

$$\sigma_r = k\frac{2P_c}{\pi Dt}, \tag{2}$$

where P_c is the critical load (the maximum load during the test) applied on the flat ends and k is the coefficient which is closely related to the loading angle 2α. When $2\alpha = 0°$, we have $k = 1$, and hence the previous formula corresponds to the original Brazilian disc. For the given value of 2α, the value of k can be determined by finite-element analysis. According to the Griffith criterion, at failure, we have $\sigma_G = \sigma_r$ so:

$$k = \frac{\sigma_G}{2P/\pi Dt}, \tag{3}$$

where σ_G is the equivalent stress based on the Griffith strength criteria. To calculate k, we used an approximate formula:

$$k = \left(2\cos^3\alpha + \cos\alpha + \frac{\sin\alpha}{\alpha}\right)^2 8\left(\cos\alpha + \frac{\sin\alpha}{\alpha}\right)\frac{\alpha}{\sin\alpha} \tag{4}$$

For $2\alpha = 20°$, we have $k = 0.9644$.

The elastic modulus E is determined with the modified formula adjusted by Wang et al. [8]:

$$\Delta w = \frac{2P}{\pi E t}\left\{(1-\mu) - \ln\left(1 + \frac{4}{\sin^2\alpha}\right)\right\}\frac{\alpha}{\sin\alpha} \tag{5}$$

This formula is inspired from the slope of the load-displacement record before the maximum load, where

- P is the resultant of the uniformly distributed force applied via the flat end (**Figure 1**)
- Δw is the displacement (mm)
- μ is the Poisson's ratio
- $\sin\alpha = \frac{2b}{D}$
- E is the elastic modulus

In this study, as shown in **Figure 1a**, the two parallel flat ends were introduced into the disc for load bearing [8]. The additional flat ends were designed with a special mould for the proposed specimen; thus, the flatness and parallelness of the flat ends are important for a successful test. A crack was adjusted in the precedent geometry to realize the second one as seen in **Figure 1b**.

Research works have proven that only when the load angle satisfies the condition $2\alpha \geq 19.5°$, the centre crack initiation can be guaranteed. This condition should be accomplished for loading the Brazilian disc specimen in the composite fracture toughness test [7]. Then, K_{IC} is determined using the proposed expression in [8], [7] and [12] as:

$$K_{IC} = \frac{P_{min}}{t\sqrt{R}}\varnothing_{max}, \tag{6}$$

where P_{min} is the minimum load, $\varnothing_{max}$ is the maximum stress intensity factor and R is the radius of the disc.

Hence:

$$\varnothing\left(\alpha, \frac{a}{R}\right) = \frac{K_I}{\frac{P}{\sqrt{R}}t}. \tag{7}$$

According to Wang and Xing [12], the SIF $\varnothing$ is calculated by the following formula:

$$\varnothing\left(\frac{a}{R}\right) = -4.2892\left(\frac{a}{R}\right)^7 - 26.6765\left(\frac{a}{R}\right)^6 + 84.9054\left(\frac{a}{R}\right)^5 - 93.087\left(\frac{a}{R}\right)^4 + 50.7763\left(\frac{a}{R}\right)^3 - 14.3776\left(\frac{a}{R}\right)^2 + 2.7408\left(\frac{a}{R}\right) \tag{8}$$

If the record indicates that the test is valid (**Figure 3**), then the fracture toughness K_{IC} can be given using the following formula [8],

$$K_{\mathrm{IC}} = 0.789 \frac{P_{\min}}{B\sqrt{\mathrm{R}}} \quad for \;\; 2\alpha = 20°, \tag{9}$$

where 0.789 is $\emptyset_{\max}$ for a loading angle $2\alpha = 20°$ calculated with Formula (8), which corresponds to the critical dimensionless crack length $a_c/R = 0.73$ as illustrated in **Figure 4**.

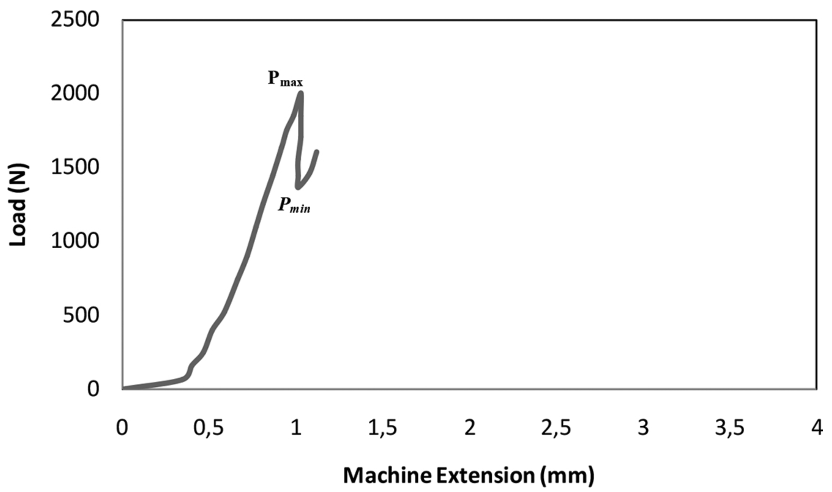


Figure 3. An example for a valid test record for the flattened Brazilian specimen.

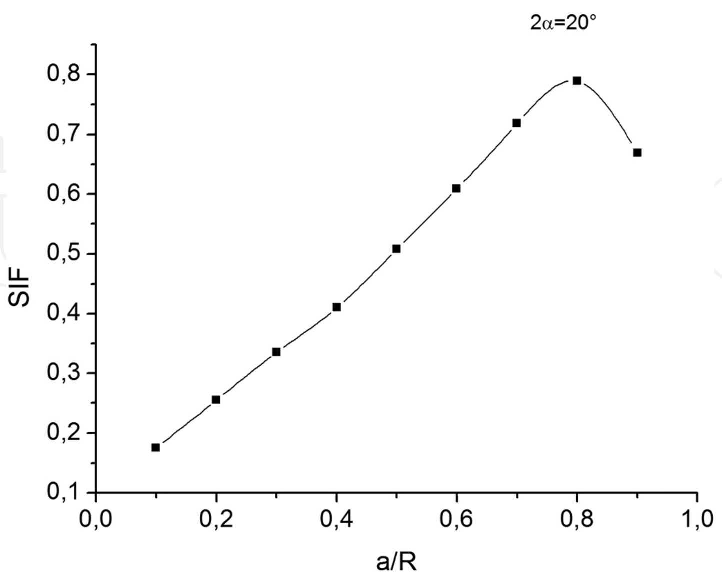


Figure 4. The dimensionless SIF versus dimensionless crack length for the flattened Brazilian disc with a central straight-through crack.

As mentioned previously, when $2\alpha \geq 20°$ the crack can be initiated at the centre of the sample, then the crack expands along the diameter. The value of the SIF gradually rises from zero (crack initiation) to the maximum where $\emptyset_{max}$ is obtained, after that $\emptyset$ decreases until the final rupture of the disc. The critical point corresponds to $\emptyset_{max}$, and the minimum load P_{min} is a turning point between the stable and unstable regions of crack development. This point coincides with the local minimum load immediately succeeding the peak load.

For brittle materials such as bioceramics, the fracture toughness K_{IC} can be considered as a material property. In fact, it requires a valid test that contains the two regions as previously mentioned and characterized with the critical point, which is the unique critical turning point immediately succeeding the top load.

4. Determination of fracture toughness of the ceramics specimen using bending test "SCB"

A new method called the cracked semi-circular bend specimen method, presented in **Figure 2**, is developed for mode I fracture toughness determination using ceramics cores. This method has recently received much attention by researchers and can be used as an alternative to the ISRM standard specimens in determining fracture mode I toughness of brittle materials because of its inherently favourable characteristics, such as simplicity, minimal machining requirements, and easy testability through the application of three-point compressive loading using a standard test frame [13–15].

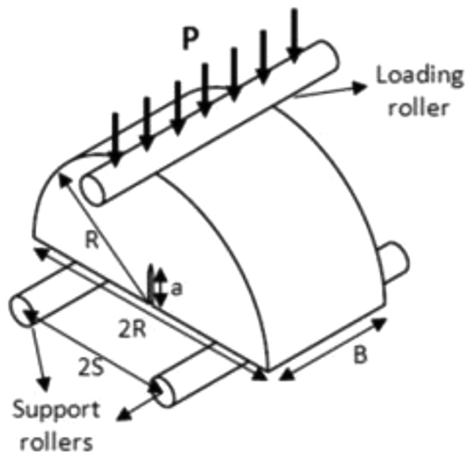


Figure 5. Semi-circular bending (SCB) specimen geometry and loading configuration.

Chong and Kuruppu [16] were among the first who suggested this specimen for conducting fracture tests on brittle materials. Since then, the SCB specimen has been employed frequently to investigate mode I fracture for composite materials. The sample has a simple geometry and can be prepared from typical ceramic cores. Little machining operations and easy test set-up procedure can be considered as major advantages of the SCB specimen.

As shown in **Figure 5**, the sample is a semi-circular disc of radius R with a single edge notch of length a manufactured from the centre of the semi-circle. Fracture test is performed by subjecting the specimen under three-point bending.

The mode I stress intensity factor K_{I} for the SCB specimen is often written as follows [17]:

$$K_{\mathrm{IC}} = \frac{P\sqrt{\pi a}}{2Rt} Y_I\left(\theta, \frac{a}{R}, \frac{S}{R}\right), \tag{10}$$

where P is the compressive applied load and t is the thickness of specimen, the mode I stress intensity factor y_I is the function of crack length ratio a/R, half-span-to-radius ratio S/R and the crack angle θ (the angle between the crack line and the vertical direction). For the pure mode I, θ is zero deg.

Chong et al. [18] also developed a formula for K_I by using both the strain energy release rate method and the elliptical displacement approach.

$$K_{\mathrm{I}} = \frac{\mathrm{P}\sqrt{\pi a}}{Dt} Y_k, \tag{11}$$

where Y_k is the dimensionless stress intensity factor as a function of the dimensionless crack length a/D, with D being the disc diameter. Y_k can be calculated by a third-order polynomial as follows:

$$Y_k = 4.47 + 7.40\left(\frac{a}{D}\right) - 106\left(\frac{a}{D}\right)^2 + 433.3\left(\frac{a}{D}\right)^3 \tag{12}$$

The precedent formula (eq. 12) is proven for:

$0.05 \le \left(\frac{a}{D}\right) \le 0.4$ and $\frac{S}{D} = 0.25, 0.305, 0.335$ or 0.4 with “s” being the loading span (**Figure 5**).

In our case, the fracture toughness K_{IC} values of SCB with straight crack are calculated with the following formula:

$$K_{\mathrm{IC}} = \frac{\mathrm{P}_{\max}\sqrt{\pi a}}{2Rt} Y_I\left(\frac{a}{R}, \frac{S}{R}\right). \tag{13}$$

where P_{max} is the maximum load, Y_I is the dimensionless stress intensity factor, t, R and a are the thickness, radius of SCB sample and crack length, respectively. Y_I, equally known as a geometry factor, is a function of the ratio of crack length over the semi-disc radius (a/R) and the ratio of half-distance between the two bottom supports "S" over the semi-disc radius (SR), which can be written as the following relation [5]:

$$Y_I = \frac{s}{R}\left(2.91 + 54.39\alpha - 391.4\alpha^2 + 1210.6\alpha^3 - 1650\alpha 4 + 875.9\alpha^5\right), \quad (14)$$

where α is $^a/_R$.

A phosphate calcium-based composite was selected for fracture toughness tests, for these semi-disc specimens of TCP-Fap having a single straight crack were subjected to three-point bending loads (**Figure 6**). Specimens were prepared by a special mould. A straight notch of 4 mm was introduced in each specimen of 15 mm radius and 5 mm thickness, the crack-length-to-diameter ratio was 0.13. The samples were placed on the loading platform, such that the span ratio S/D was 0.36, and then were tested to failure under load-line displacement control and at a loading rate of 0.075 mm/min. The load and load-point displacement (LPD) was recorded as a function of time during each test. A LLOYD machine with a capacity of 5 kN was used for conducting the fracture tests on the SCB specimens.

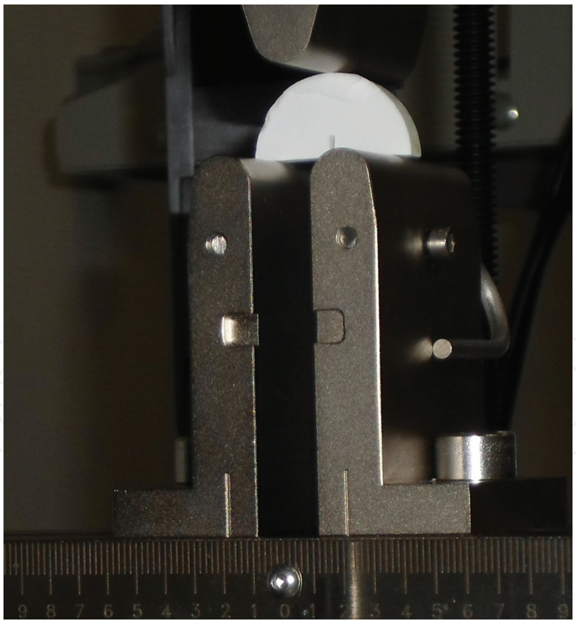


Figure 6. Semi-circular bend (SCB) test specimen.

As shown in the above figure (**Figure 6**), the test procedure in SCB specimens seems easy and cost effective and permits the determination of K_{IC}3 for investigating the material behaviour under loading.

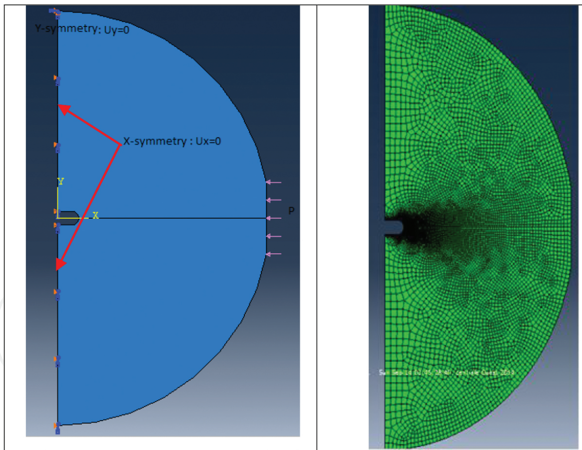
5. Numerical computations

Modelling work was done by using ABAQUS finite-element program. In this part, to evaluate the stress intensity factor around the crack tip, a contour integral region is defined and K_I values in this region are computed. In fracture modelling, crack tips are regions of high stress gradients and high stress concentrations, and these concentrations result in theoretically infinite stresses at the crack tip [19]. Hence, to get accurate stresses and strains near the crack tip, finite-element mesh must be refined around the crack tip. The final K_I value at the crack tip is calculated by averaging the K_I values determined for a user-specified number of crack tip concentric mesh rings in the contour integral region.

The mechanical properties were chosen to represent the composite specimens, for which elastic modulus and Poisson's ratio are 31.3, 38.5, 44.5, 60.7 and 66.4 GPa and 0.242, 0.203, 0.286, 0.228 and 0.273, respectively.

5.1. CSTFBD model

Numerical modelling is used for estimating stress intensity factors for Brazilian disc geometry. The flattened Brazilian specimens with a central straight-through crack were used for numerical investigation of mode I fracture in the shaped notches. Since the flattened Brazilian tests do not need 3D modelling the 2D analyses were conducted. To simplify the model, half of it was drawn and the symmetry option was used.



(a) (b)

Figure 7. (a) Boundary conditions of the specimen and (b) FE grid generation for the flattened Brazilian specimen with a central straight-through crack.

2DTwo-dimensional-plane strain analyses were performed in this work with a total number of 37,953 Quad 8 elements to simulate the specimen. **Figure 7a** shows the ABAQUS model with

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different boundary conditions. A large number of elements were used near the crack tip due to its high stress gradient. **Figure 7b** shows a sample FE grid pattern used for the simulation of flattened Brazilian specimen with a central straight-through crack.

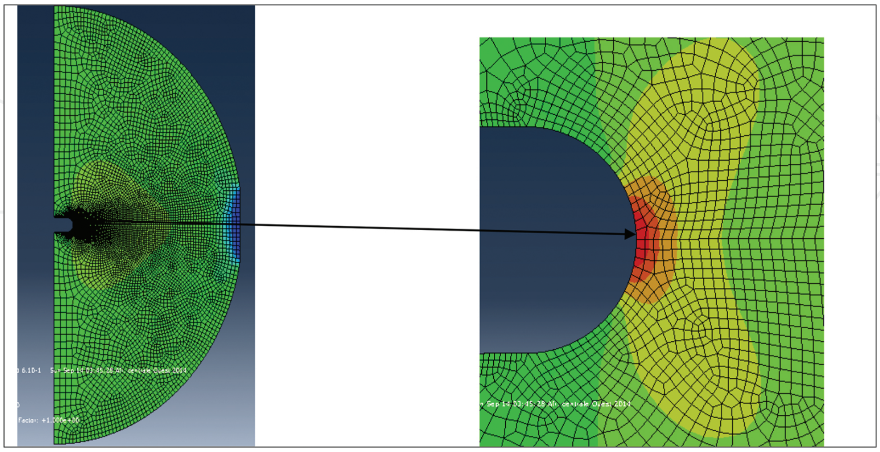

Figure 8. Stress distribution for the flattened Brazilian disc: Distribution of the stress from the crack tip to the parallel flat.

The stress distributions for the flattened Brazilian test and the change of vertical stress while moving away from the crack tip to the parallel flat are revealed in **Figure 8**. These distributions allow the identification of the most stressed area under tensile stresses. The vertical stress $\left(\sigma_{yy}\right)$ is the largest at the crack tip, and it decreases while moving away from the crack tip in the direction of crack propagation. Therefore, the initiation of the crack by tension arises in the disc centre. Actually, many factors contribute to the fact that cracks can be initiated in any place other than the disc centre like material inhomogeneity, which causes local strength variation and the accuracy of specimen preparation, especially the degree of parallelism and loading boundary conditions. All these factors may influence the crack initiation point.

The value of stress intensity factor K_I is given for all compositions for different crack lengths (see **Figure 9**).

The numerical calculation shows that the variation of SIF is similar for all compositions. We have the same trend for every curve. The stress intensity factor K_I increases gradually to reach the maximum. When K_I reaches its maximum value, we have the critical dimensionless crack length ${}^{a_c}\!/_{R}$ corresponding to 0.73. Finally, the K_I decreases until the final breakage of the disc. It is clear that the curve is formed of three regions where K_{Imax}, which corresponds to the fracture toughness for every sample, constitutes the intermediate region. In the first region, when K_I increases progressively, we have also an unstable crack growth because of the evolution of the crack when the load is held constant. In the third region, after the achievement of K_{Imax}, K_I decreases and the crack growth becomes stable [7].

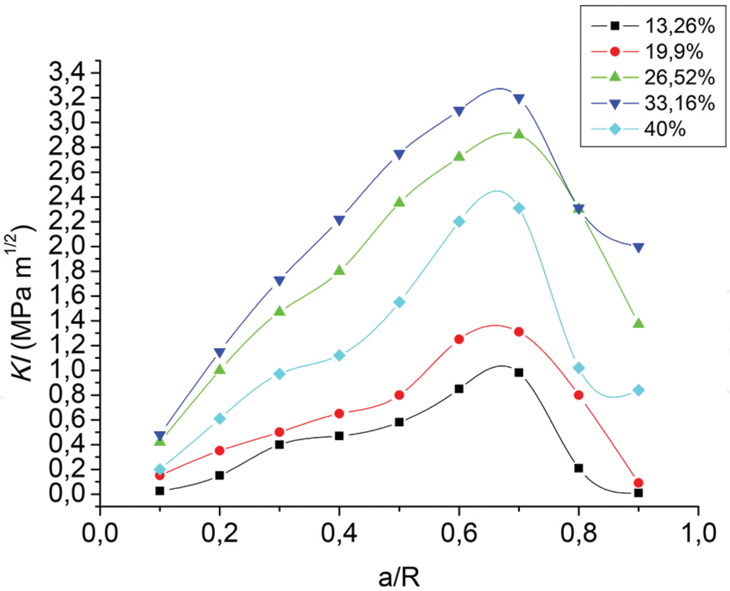

Figure 9. The stress intensity factor versus dimensionless crack length for the flattened Brazilian disc with a central straight-through crack with different percentages of Fap.

5.2. SCB model

In order to compute the stress intensity factor K_I, it is necessary to create an appropriate finite-element model of the specimens that are considered for performing the fracture tests. In this part, the cracked semi-circular (SCB) specimens were performed for numerical calculation of mode I. Two-dimensional modelling of the SCB is used in this work to simulate the specimen and calculate the distribution of stress intensity factor at the crack front, and a large number of elements were used near the crack tip due to its high stress concentration. A typical 2D finite-element modelling of the SCB sample can be seen in **Figure 10a**. Approximately, 5800 Quad 8-node 2D elements were used to mesh this model. As mentioned previously, because of singularity at the crack tip, the elastic singular elements and finer mesh were used around the crack tip as shown in **Figure 10b**.

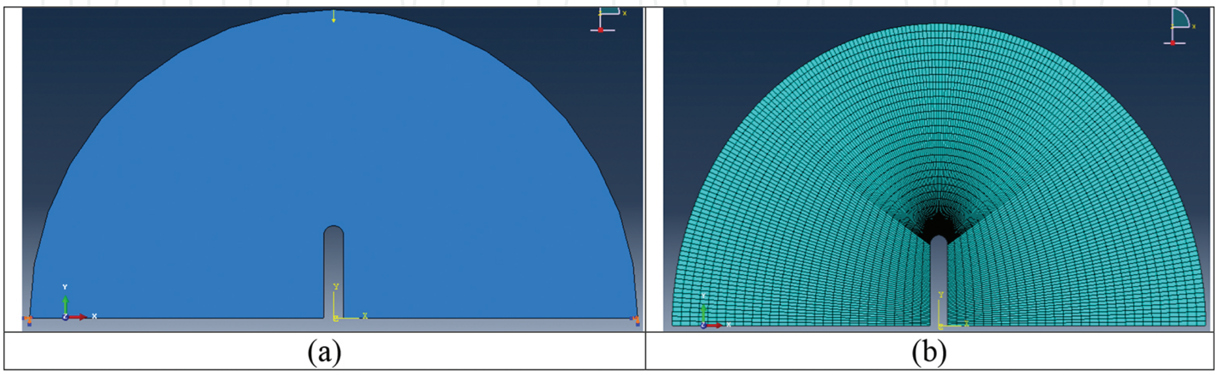

Figure 10. 2D modelling of the SCB specimen.

As the CSTFBD specimen, the vertical stress (σ_{yy}) is the largest at the crack tip and it decreases while moving away from the crack tip in the direction of crack propagation. Therefore, the initiation of the crack by bending test also arises in the centre. After the crack starts from the semi-circular bend centre at the maximum load, the crack propagates symmetrically ahead the loading direction.

The distribution of the stress intensity factor along the crack front for all compositions for different crack lengths is plotted in **Figure 11**.

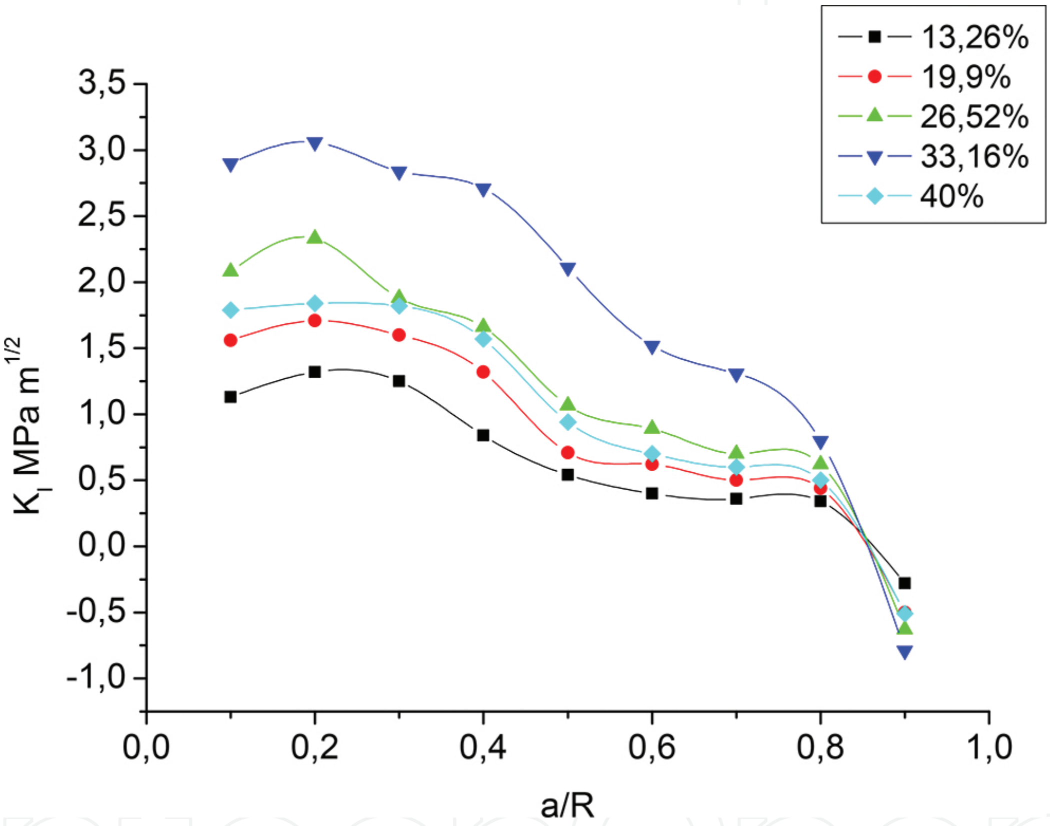

Figure 11. The numerical calculation of the SIF in the SCB specimen versus dimensionless crack length.

As shown in **Figure 11**, the same trend was repeated for different compositions of the ceramic elaborated: The variation of SIF is similar for all compositions. It can also be observed from this figure that the stress intensity factor of the SCB specimen with straight crack first increases until $a/R = 0.2$ and then decreases when the dimensionless crack length exceeds 0.2. In fact, due to the high stress gradient at the crack tip of the specimen, the crack grows sub-critically at first; then after reaching a critical value ($a_c = 0.2$), unstable crack growth occurs rapidly and final failure takes place in the sample. For $\alpha > 0.8$, K_I reaches negative values which affirmed the notice reported by Ayatollah and Aliha [14] that the mode I stress intensity factor in SCB specimens becomes negative for higher values of a/R.

6. Analytical results and discussion

6.1. Determination of elastic modulus *E* and tensile strength σ_t for valid flattened test

In this part, we used the flattened Brazilian disc without crack. By applying the previous formula Eq. (5), the elastic modulus *E* is calculated for different percentages of fluorapatite additive.

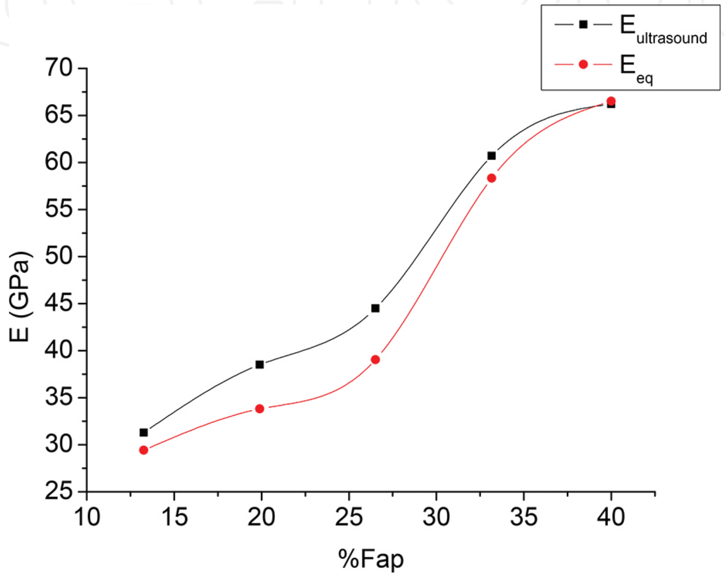

Figure 12. Elastic modulus versus percentage of Fap under optimal conditions.

The calculated values are compared with those found by ultrasound [20], which, as shown in **Figure 12**, was found to be in good compromise.

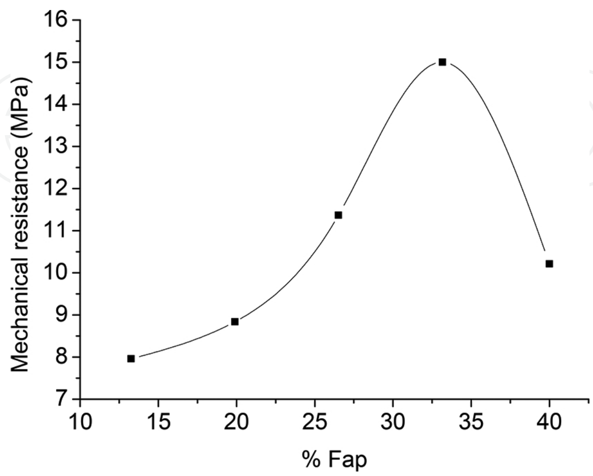

Figure 13. Mechanical resistance versus percentage of Fap of β-CTCP wt% Fap composites sintered at 1300°C for 1 h 30 min.

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Figure 13 illustrates the evolution of the mechanical resistance in relation to the percentage of Fap under optimal conditions. According to the work of Bouslama [20], the previously used composite samples reached their optimum at 1300°C, which justifies our choice of sintering temperature. This is attributed to the influence and effect of Fap in the mechanical resistance of the sintered composites. In addition, Fap has good sinterability and mechanical resistance [21]. Ben Ayed et al. (2000a, 2001b, 2006c) have illustrated that the mechanical resistance of Fap increases with temperature and reaches its maximum value at about 14 MPa [9, 21, 22].

In treating the experimental data, the mechanical properties of composites were determined as a function of the sintering temperature. At 1300°C, the rupture strength increases with the percentage of Fap and reaches a maximum value of 33.16% (15 MPa) at 1300°C. Bouslama et al. [23] explained the fall of tensile strength for 40% Fap by the important intergranular porosity existing in the composite's microstructure. It is obvious that the mechanical properties of TCP-Fap composite are also affected by different parameters and operative conditions like temperature, the cycle of sintering, heating time, atmosphere and the presence of micro-crack.

6.2. Determination of the fracture toughness using CSTFBD test

It should be noted that we used different samples sintered under optimal conditions. An experimental–numerical method is proposed to measure bioceramic fracture toughness for flattened Brazilian disc with a central straight-through crack.

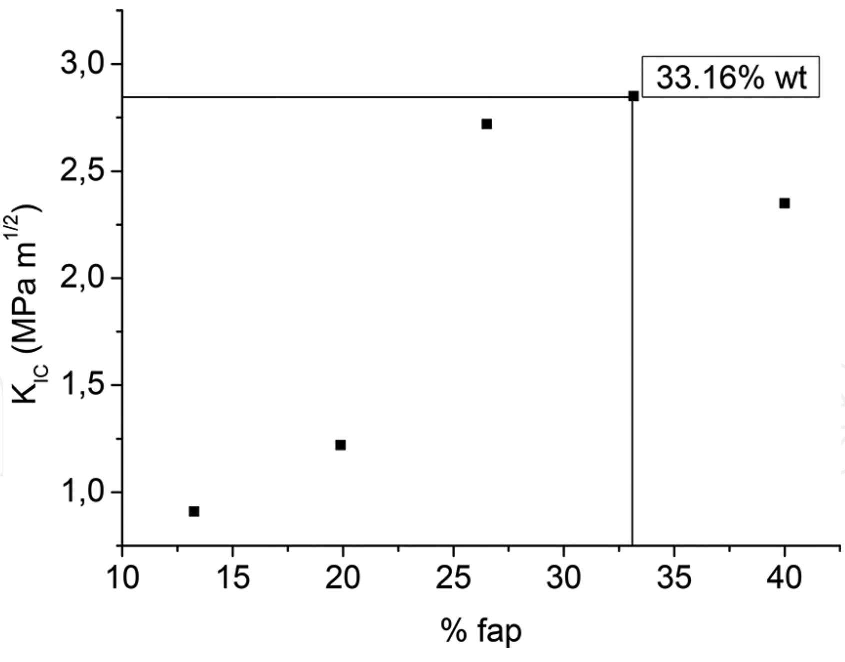

Figure 14. Fracture toughness versus %wt Fap for the CSTFBD specimen.

After the crack starts from the disc centre at the maximum load, the crack propagates symmetrically ahead the loading diameter. Then, the specimen develops into the flattened Brazilian disc with a central straight-through crack, for which there is no stress intensity factor solution in the literature [8]. Thus, we used the finite-element method for the computation of the stress intensity factor. Analytical analysis for this specimen is performed by using Eq. (9). Toughness fracture variation is presented in **Figure 14**.

The fracture toughness values of CTCP-wt% Fap composites range between 0.9 and 2.7 MPam. The lowest toughness (0.9 MPam) is obtained with the 13.26 %wt Fap, while the highest one is approached with the 33.16 %wt fap (2.7 MPam). These results agree well with the mechanical properties evolution of a similar sample sintered under optimal conditions (**Figure 13**), in which the rupture strength reaches maximum when 33.16 wt% Fap are added to the ß-CTCP.

Since Eq. (7) is created, any load P and its corresponding crack length a/R can be placed in this equation to determine the fracture toughness. Luckily, as mentioned above, for the flattened Brazilian disc with a central straight-through crack, the evolution of its stress intensity factor over crack propagation is unique. Indeed, referring to **Figure 4**, ∅ has a maximum value « $\emptyset_{max}$», which should correspond to a minimum value of load P_{min} (**Figure 3**), which can be easily detected from the load-displacement record.

From the above observation, we come to the conclusion that the assumption of elastic behaviour is determined for the flattened Brazilian test. In fact, the crack initiates from the disc centre and propagates mostly along the loading diameter until the two flat ends. In this way, the disc is broken into two parts as presented in **Figure 15**, while the vacant regions close to the two flat ends involve the existence of crush zones. However, these crush zones developed after the crack initiation at the centre and below the propagation along the diameter. The validity of the flattened Brazilian test is thus further justified experimentally.

Figure 15. (a) CSTFBD before testing and (b) failure mode of CSTFBD specimens.

6.3. Determination of the fracture toughness using bending test

The tests were carried out using the SCB sample configuration shown in **Figure 5**. It should be also noted that bending tests were performed by employing different specimens sintered under optimal conditions. An experimental-analytical method is proposed to investigate the mode I bioceramic fracture toughness for the SCB specimen. Analytical analysis for this geometry is accomplished by using Formula 13. **Figure 16** presents the test results for the calculation of the fracture toughness for the same crack length with different percentages of Fap. Six specimens were performed at each percentage additive. Results of experiments were compared with the results of well-known mode I fracture toughness testing methods.

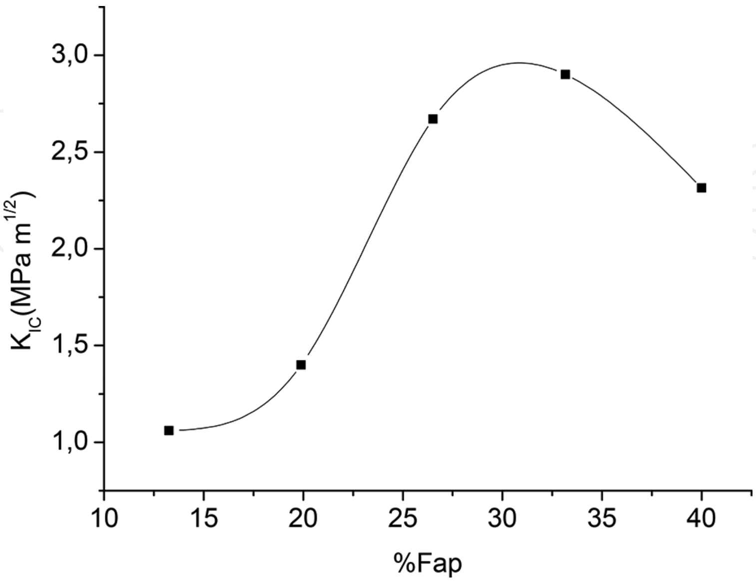

Figure 16. Fracture toughness versus %wt Fap for the SCB specimen.

The fracture toughness values of CTCP-wt% Fap composites range between 1.06 and 2.9 MPam. The lowest toughness (1.06 MPam) is obtained with the 13.26 wt% Fap, while the highest one is approached with the 33.16 wt% Fap (2.9 MPam).These results agree well with the numerical computation effected in the precedent section (**Figure 11**), in which the stress intensity factor reaches maximum when 33.16 wt% Fap are added to the β-CTCP. The mode I fracture toughness measured using SCB specimens is closer to that measured in the precedent section using a flattened Brazilian disc with central straight-through crack (CSTFBD) specimens (2.7 MPam).The variation of the fracture toughness value was due to the differences in the size of the fracture process zone (FPZ) [16]. Aliha et al. [24] reported that the fracture toughness heavily depends on the geometry and loading conditions of the test specimen, for that the fracture toughness of the composite measured using the CSTFBD sample was a little less than that measured using a SCB specimen. Advantages of this new method included easy sample preparation and testing procedure and smaller fracture process zone.

7. Conclusion

The aim of this work is to study the fracture behaviour of the Fap-β-CTCP.

One of the specimens to determine the fracture toughness of bioceramics is the semi-circular bend (SCB) with straight crack. Stress intensity factor at the crack front is an important parameter to find the fracture toughness. On the other hand, a CSTFBD sample is an ideal specimen to be also used for measuring the fracture toughness.

A finite-element modelling study was conducted to evaluate crack propagation in the SCB and CSTFBD specimen during loading. The numerical modelling results are validated by comparing with experimental ones which showed the same outcome for both methods.

Based on the results of both experimental and numerical investigations, the following concluding remarks for the novel configuration Brazilian test can be noticed:

- Three parameters (E,σ and K_{IC}) can be determined in only one test record. E is obtained from the approximate analytical solution for the displacement of the loaded flat end, and when the Poisson's ratio μ is known, the elastic modulus is calculated from the slope of the section of loading-displacement record just before the maximum load. Furthermore, tensile strength is measured from Formula (2) by inserting P_{max} and the coefficient k . Finally, the fracture toughness K_{IC} is determined using the clearly local minimum load P_{min} corresponding to the maximum value of dimensionless stress intensity factor $\emptyset_{max}$ and Eq. (6) is applied.
- The guarantee of the centre crack initiation for the loading angle which satisfies the condition of $2\alpha \geq 20°$: the centre crack initiation being important for test validity.
- The effectiveness and reliability of the new test method for bioceramics fracture test have been demonstrated.

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