Similarities Analysis on Hydroxyapatite-Zirconia Composites

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Abstract

Hydroxyapatite ($Ca_{10}(PO_4)_6(OH)_2$) is one of the implants materials with medical applications due to its higher biocompatibility. The hydroxyapatite found complete utilization after proper preparation of composite. The influence of zirconia (ZrO_2) on the phase composition and on mechanical properties of hydroxyapatite-zirconia composites has been previous investigated and reported. Hierarchical cluster analysis methods were applied in order to assess the similarities of four different types of hydroxyapatite-zirconia composites. Four classes of composites (hydroxyapatite, hydroxyapatite coarse-grained zirconia, hydroxyapatite fine-grained zirconia, and hydroxyapatite needle-grained zirconia) cumulating a total number of sixteen experiments were analyzed. A number of nine quantitative variables were included into analysis: sintering temperature, Vickers hardness, bending strength, characteristic strength, Weibull modulus, anisotropy, Young's modulus, rigidity modulus, and Poisson ratio. Data were analyzed using SPSS software by applying cluster analysis techniques. The analysis revealed interesting information regarding similarities between studied hydroxyapatite-zirconia composites.

Keywords

Hydroxyapatite (HAp); Zirconium Dioxide (zirconia, ZrO_2); Cluster Analysis

Abbreviations

HAp = hydroxyapatite; HAp-CGz = hydroxyapatite coarse-grained zirconia composite; HAp-FGZ = hydroxyapatite fine-grained zirconia composite; HAp-NGZ = hydroxyapatite needle-grained zirconia composite.

Introduction

Hydroxyapatite ($Ca_{10}(PO_4)_6(OH)_2$) is one of the implants materials with medical applications due to its higher biocompatibility. In medicine, hydroxyapatite found its utility as material used to create implant materials (based on its ability to create firm bond with bone tissue) [1,2] and in development of drug delivery systems [3,4]. The hydroxyapatite found complete utilization after proper preparation of composite. Zirconium dioxide of (ZrO_2), as powders and fibers, due to the martensitic transformation of tetragonal to monoclinic ZrO_2 [5], is used in reinforcing phases based on its good toughness [6]. When zirconia's is use to reinforce hydroxyapatite composite, the properties of both materials are combined advantageously [7].

Hierarchical cluster analysis, a statistical method for finding relatively homogeneous clusters of cases based on measured characteristics, is used today in many domains including in medicine [8-11]. It is the method able to identify the relationship among entities by constructing a hierarchy or tree-look structure based on an ordering concept [12].

Starting with the possibilities offered by the hierarchical clustering approach, the goal of the present research was to analyze the similar characteristics of hydroxyapatite and three hydroxyapatite-zirconia powders with different phase composition, shape and size of grains.

Material and Method

Hydroxyapatite and hydroxyapatite-zirconia composites

The data regarding the hydroxyapatite-zirconia (HAp-ZrO2) composite were taken from a previous reported research [13]. There were investigated nine variables (see also Table 1):

- Sintering temperature (temperature applied for making objects from hydroxyapatite and hydroxyapatite-zirconia powders);
- Vickers hardness (ability to resist plastic deformation);
- Bending strength (upper limit of normal stress of a beam at which fracture or excessive deformation occurs);
- Characteristic strength and Weibull modulus (the degree of reliability of materials). Weibull Modulus is a dimensionless number used to characterize the variability in measured strength of components made from hydroxyapatite and hydroxyapatite-zirconia composites which arises from the presence of flaws having a distribution in size and orientation
- Anisotropy (non-destructive measurements of the speed of propagation of ultrasonic waves in directions perpendicular and parallel to the axes);
- Young's modulus (physical property of being inflexible and hard to bend);
- Rigidity modulus (physical property of being stiff and resistant to bend);
- Poisson ratio (ratio between the strain of expansion in the direction of force and the strain of contraction perpendicular to that force).

Table 1. Hydroxyapatite and hydroxyapatite-zirconia composite experimental data

No	Composite	Sintering Temperature [°C]	Vickers Hardness [GPa]	Bending Strength [MPa]	Characteristic Value [MPa]	Weibull Modulus	Anisotropy [%]	Young's Modulus [GPa]	Rigidity Modulus [GPa]	Poisson Ratio
1	HAp	1150	5.8	101.2	108	8.8	1.52	119.5	46.5	0.285
2		1200	6.4	98.6	106	7.9	2.5	119.3	46.2	0.291
3		1250	6.6	89.5	93	8.2	1.97	119.3	46.4	0.287
4		1300	5.7	84.3	89	8.3	1.63	118.8	46.2	0.285
5	HAp-CGZ	1150	6.8	121.6	126	9.9	0.79	128.1	50	0.282
6		1200	6.4	119.1	128	9.1	0.44	127.7	19.9	0.281
7		1250	6.7	125.9	130	9.3	0.71	125.6	19	0.282
8		1300	6.5	130.8	134	9.9	0.55	125.7	19	0.283
9	HAp-FGZ	1150	7.4	120.4	122	7.3	1.5	128.1	50	0.281
10		1200	7.6	125.2	133	7.8	1.19	126.9	19.4	0.283
11		1250	6.5	100.6	108	6.7	1.46	126.7	49.5	0.279
12		1300	6.1	97.1	103	7.2	0.98	126	49.2	0.28
13	HAp-NGZ	1150	7.1	129	134	9.1	0.16	127.6	49.7	0.284
14		1200	7.3	123.9	131	7	0.98	128.1	50	0.28
15		1250	7.1	101.2	104	7	1.09	126.6	49.3	0.283
16		1300	6.9	110.9	113	9.2	1.59	127.3	49.5	0.286

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Hierarchical cluster analysis

Hierarchical clustering method was applied using SPSS software version 12 in order to analyze the similarities of hydroxyapatite and hydroxyapatite-zirconia composite obtained at different sintering temperature.

From the range of the cluster analysis methods there was choused to work with hierarchical cluster method for identification of similarities on the hydroxyapatite and hydroxyapatite-zirconia composite. This method has been choused because:

a. The goal of the research was to identify and analyze similarities between hydroxyapatite and hydroxyapatite-zirconia composite based on a series of continuous variables;
b. It is an easy to implement well-documented method;
c. Provides as result dendrograms, tree-like structures that illustrate the relationships between the entries.

The following questions were formulated in order to reach the goal of the research: What defines inter-sample similarity?, What define the clusters?, How to use clusters?, and What explains the clusters?

The squared Euclidian distance has been applied on the data in order to identify the similarities. There has been choused to work with this approach due to its main advantage: the distance between any two objects is not affected by the addition of new objects to the analysis.

Results

All sixteen experimental data were valid and thus were included into the analysis. Squared Euclidean distances were computed, and the obtained proximity dissimilarity matrix is presented in Table 2.

The agglomeration schedule is presented in Table 3.

In order to summarize the clustering steps, the icicle plot has been generated and is presented in Figure 1.

The visual representation of the distance at which the clusters are combined is graphically represented by dendrogram (see Figure 2).

Table 2. Squared Euclidean distance: proximity matrix

Exp.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	0														
2	2513	0													
3	10363	2752	0												
4	23147	10495	2544	0											
5	829	3528	12214	25366	0										
6	3997	1672	5377	13505	3417	0									
7	11889	4606	3487	6700	11002	2556	0								
8	24849	12609	6683	4979	23616	10178	2540	0							
9	656	3325	11888	24997	25	3449	11067	23727	0						
10	4495	2216	6163	14397	3505	67	2515	10040	3582	0					
11	10066	2576	415	3203	10778	4126	2063	5030	10591	4639	0				
12	22594	10068	2713	422	23642	11974	4975	3016	23411	12581	2538	0			
13	1528	4297	13325	26618	120	3523	10973	23450	223	3437	11491	24487	0		
14	3636	1361	5221	13438	2539	944	3478	11033	2594	944	3575	11509	2540	0	
15	10079	2577	322	3085	10911	4267	2211	5204	10696	4812	17	2519	11679	3747	0
16	22690	10278	3433	1369	22786	11170	3948	1772	22676	11513	2638	297	23271	10499	2681

1150 °C sintering temperature: 1 = HAp; 5 = HAp-CGZ; 9 = HAp-FGZ; 13 = HAp-NGZ

1200 °C sintering temperature: 2 = HAp; 6:HAp-CGZ; 10 = HAp-FGZ; 14:HAp-NGZ

1250 °C sintering temperature: 3: = HAp; 7 = HAp-CGZ; 11 = HAp-FGZ; 15 = HAp-NGZ

1300 °C sintering temperature: 4 = HAp; 8 = HAp-CGZ; 12 = HAp-FGZ; 16 = HAp-NGZ

Table 3. Hydroxyapatite and hydroxyapatite-zirconia composites: agglomeration schedule

Stage	Cluster Combined		Coefficients	Stage Cluster First Appears		Next Stage
	Cluster 1	Cluster 2		Cluster 1	Cluster 2	
1	11	15	16.997	0	0	6
2	5	9	25.064	0	0	4
3	6	10	66.793	0	0	8
4	5	13	171.826	2	0	9
5	12	16	297.232	0	0	7
6	3	11	368.577	0	1	12
7	4	12	895.712	0	5	12
8	6	14	943.993	3	0	10
9	1	5	1004.364	0	4	13
10	2	6	1749.603	0	8	13
11	7	8	2540.446	0	0	14
12	3	4	2817.149	6	7	14
13	1	2	3398.580	9	10	15
14	3	7	4172.476	12	11	15
15	1	3	12634.632	13	14	0

Cluster no	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
8:HAp-CGZ	X	X	X	X	X										
7:HAp-CGZ	X	X													
16:HAp-NGZ	X	X	X	X	X	X	X	X	X	X	X				
12:HAp-FGZ	X	X	X	X	X	X	X	X	X						
4:HAp	X	X	X	X											
15:HAp-NGZ	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
11:HAp-FGZ	X	X	X	X	X	X	X	X	X	X					
3:HAp	X														
14:HAp-NGZ	X	X	X	X	X	X	X	X							
10:HAp-FGZ	X	X	X	X	X	X	X	X	X	X	X	X	X		
6:HAp-CGZ	X	X	X	X	X	X									
2:HAp	X	X	X												
13:HAp-NGZ	X	X	X	X	X	X	X	X	X	X	X	X			
9:HAp-FGZ	X	X	X	X	X	X	X	X	X	X	X	X	X	X	
5:HAp-CGZ	X	X	X	X	X	X	X								
1:HAp	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X

Figure 1. Hydroxyapatite and hydroxyapatite-zirconia composites: icicle plot

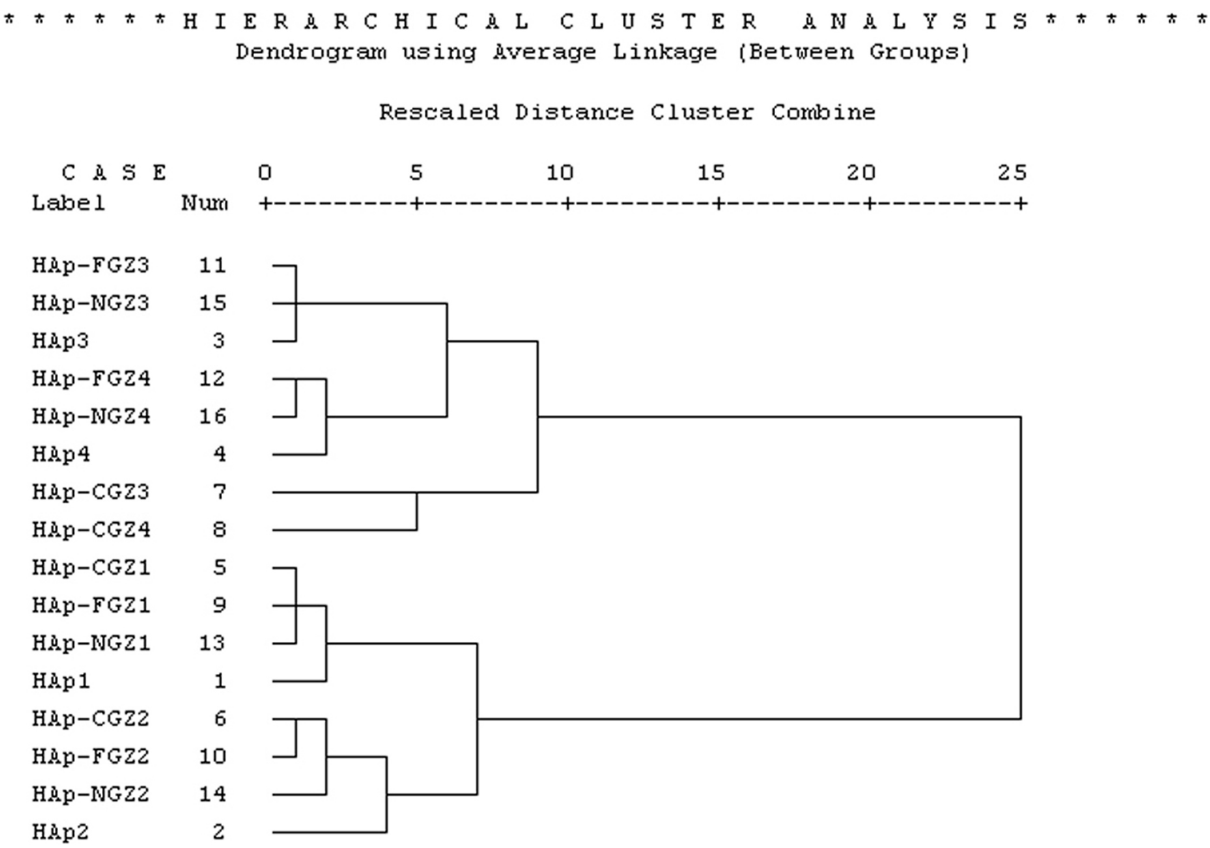

Figure 2. Hydroxyapatite and hydroxyapatite-zirconia composites: dendrogram

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Discussion

In the last decade the clustering methods was been used to classify small and large amount of information [14-16]. There are many clustering algorithms but a little consensus exists regarding the best algorithm. Due to the aim of the present research, in order to joining similar observations the agglomerative average linkage method (the average distance from samples is used in one cluster to samples in other clusters [17]) has been applied. The results shown hydroxyapatite and hydroxyapatite-zirconia composites could be classified using hierarchical cluster analysis method.

The hydroxyapatite and hydroxyapatite-zirconia ceramics are used as implant materials in medicine especially as artificial bones [19-22]. It is well known that probability law governs ceramics mechanical properties and the mathematical strength should be assumed as a random variable [23].

A series of variables used to characterize the ceramic properties were investigated using hierarchical cluster analysis method. Sintering temperature, four elasticity parameters and four mechanical parameters of hydroxyapatite and hydroxyapatite-zirconia composite had been analyzed.

Analyzing the proximity matrix of squared Euclidean distance, it can be observed that the smaller distance (as measures of how far apart two object are) were obtained in ascending order by:

- HAp-FGZ & HAp-NGZ (both at 1250°C sintering temperature), see Table 1. For this two composite the smaller differences were identified for Poisson ratio (0.004), Young's modulus (0.1 GPa), rigidity (0.2 GPa), Weibull modulus (0.3 MPa), anisotropy (0.37%), while the greatest value was obtained for characteristic value (4 MPa)
- HAp-CGZ & HAp-FGZ (both at 1150°C sintering temperature): have identical values for parameters that refer the inflexibility and hardness to bend and stiff and resistance to bend, and a very small differences of Poisson ratio (absolute difference of 0.001, see Table 1). Comparing with previous pair of composite greater values was obtained for bending strength, Weibull parameter and anisotropy.
- HAp-CGZ & HAp-FGZ (both at 1150°C sintering temperature): have the smallest difference for Poisson ratio (absolute difference of 0.002, see Table 1) and small absolute differences of stiff and resistance to bend (0.5 GPa, see Table 1), anisotropy (0.75 %, see

Table 1), and of inflexibility and hardness to bend (0.8 GPa, see Table 1). Comparing with previous-presented pairs, greater values are obtained for absolute differences of ability to resistant plastic deformation (1.2 GPa, see Table 1), bending strength (6.1 MPa, see Table 1), characteristic strength (5 MPa, see Table 1), anisotropy, inflexibility, hardness to bend, stiffness, and bending resistance.

- Note that the sintering temperature had the save value for all three pairs of composite for which the small distance was obtained.
- The greater values in descending order were obtained by:
- HAp (1300°C sintering temperature) & HAp-NGZ (1150°C sintering temperature): a value of absolute difference of 45 MPa is obtained for characteristic strength, of 44.7 MPa for bending strength, of 1.47 % for anisotropy, of 8.8 GPa for inflexibility and hardness to bend and of 1.4 GPa for Vickers hardness
- HAp (1150°C sintering temperature) & HAp-CGZ (1300°C sintering temperature)
- HAp-FGZ (1300°C sintering temperature) & HAp-NGZ (1150°C sintering temperature)

The cases were considered as alike or similar for small distance on squared Euclidean distance proximity matrix.

The analysis of what happen at each clustering step can be performed through icicle plot (see Figure 1). The icicle plot presented in Figure 1 shown that in the first step the HAp-FGZ & HAp-NGZ (1250°C sintering temperature) are linked together to form a cluster (note that the distance between composites is the smaller one). At the next step the second cluster in formed starting with HAp-FGZ (1150°C sintering temperature) composite (the value of the squared Euclidean distance is next as value after the smallest distance, see Table 2). The next composite that joined to the clusters is HAp-FGZ (1200°C sintering temperature). The process continues until all composite are included into one cluster or another.

A visual representation of the above-described process is presented in Figure 2. In first clustering step there are obtained four clusters (two that incorporate three composite and two that incorporate two composite) at a rescale distance of one. Analyzing the variable that is common to the formed clusters it can be observed that two clusters link together three out of four composite at sintering temperature of 1150°C (HAp-CGZ&HAp-FGZ&HAp-NGZ, cluster 1.1.) and at 1250°C (HAp&HAp-FGZ&HAp-NGZ, cluster 1.2.) while two clusters link together two out of four composite at sintering temperature of 1200°C (HAp-CGZ&HAp-FGZ, cluster 1.3.) and 1300°C (HAp-FGZ&HAp-NGZ, cluster 1.4.) respectively.

First cluster (1.1.) joined hydroxyapatite-zirconia composite that had similar values of Poisson ration, anisotropy, having similar stiffing and resistance to bend, abilities to plastic deformations and reliability. The second cluster (1.2.) bring together three hydroxyapatite-zirconia composite prepared at 1150°C that had values very closed to each other for Poison ratio, and similar stiffness and resistance to bend and abilities to resist to plastic deformation. The third and fourth clusters (1.3. and 1.4.) joined hydroxyapatite-zirconia composite that had values of Poisson ration very close to each other (in the cluster), stiffness and resistance to bend and inflexibility and hardness to bend, respectively.

At a rescaled distance of two, three clusters are formed:

- 2.1. – Joined the cluster 1.1 with HAp (at 1150°C sintering temperature): all included composite are sintering at 1150°C. The values of the Poisson ratios were very close to each other as well as the parameter of stiffness and resistance to bend.
- 2.2. – Joined the cluster 1.3 with HAp-NGZ (at 1200°C sintering temperature): the same observation as above is applied here too.
- 2.3. – Joined the cluster 1.4 and HAp (at 1300°C sintering temperature): the same observation as above is applied here too.

Note that at this level hydroxyapatite at two different sintering temperatures are joined for the first time into a cluster.

Another cluster is formed at a rescaled distance of four, when the hydroxyapatite and hydroxyapatite-zirconia composite at a sintering temperature of 1200°C are joined (cluster no. 3). At a rescaled distance of five two hydroxyapatite-zirconia composite, the HAp-CGZ at 1250°C and at 1300°C sintering temperatures, with small differences at the level of all investigated parameters (cluster no. 4, see Table 1) formed a cluster. The cluster no. 1.2 is joined with the cluster no. 2.3 to form the fifth cluster at a rescale distance of six (see Figure 2). The entire composite included into this cluster had closed values for the following parameters: Poison ratio, stiffness and resistance to bend, inflexibility and harness to bend and resistance to plastic deformation. The difference of sintering temperature is of 50°C.

By joining the cluster 2.1 with cluster no 3, the sixth cluster is formed at a rescale distance of seven; and by joining the cluster no 4 and 5 at a rescaled distance of nine, the seventh cluster is formed. Cluster number six joined the hydroxyapatite and hydroxyapatite-zirconia composite sintered at 1150°C and 1200°C while the cluster number seven the hydroxyapatite and hydroxyapatite-zirconia composite sintered at 1250°C and 1300°C. Note that all clusters are formed at a rescaled distance less than ten, sustaining the existence of similarities between studied hydroxyapatite and hydroxyapatite-zirconia composite.

The hierarchical cluster method identify that sintering temperature is the most important variable used in clusterization, followed by Poisson ration. Other four parameters (out of nine) with importance in clusterization were Vickers hardness, anisotropy, Young's modulus and rigidity modulus. Note that the degree of reliability of hydroxyapatite and hydroxyapatite-zirconia were not considered in clusterization by any cluster.

It can be concluded that hierarchical cluster approach is useful in identification and characterization of similarities of studied hydroxyapatite and hydroxyapatite-zirconia composites. A detailed analysis of all characteristics of ceramics used as implants materials in medicine could reveal information useful in practice.

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