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Abstract: A new biodegradable, sustainable and environmentally friendly building material is introduced and studied in this work, which can be applied to lightweight architectural structures, aiming for the reduction of the greenhouse gas emissions and mitigation of the climate change effects. The focus was to investigate the effect of water concentration and different types of sand on the mechanical properties of corn starch-based artificial sandstone. A series of cubic, cylindrical and disk specimens were prepared by varying the concentration of water and using different sources of commercial quartz sand. The quasi-static and cyclic compressive properties of starch-based artificial sandstone samples were measured as a function of water concentration and sand type, while the structure of the artificial sandstone specimens was examined by scanning electron microscopy (SEM) and optical microscopy. Moreover, the Brazilian Test was employed as the indirect method to determine the tensile strength of the samples based on the type of the commercial sand they contained. The experimental results showed that the homogeneous grading of sand grains and the latter’s chemical composition have a significant effect on the mechanical properties of the sandstone samples. The highest compression values were obtained using the microwave heating method at a water concentration of about 12 wt%, while the cyclic compression and Brazilian Tests have shown that the granulometric grading of the sand particles and the chemical composition of the sand influence the compressive and tensile strength of the material.

Keywords: maize starch; starch-based sandstone; artificial sandstone; mechanical properties; bio composite structure material

1. Introduction

Due to the increased greenhouse gas emissions and the subsequent rise in global temperature, global warming has become an urgent threat to human life. Studies have shown that mortality have increased the past thirty years due to climate change [1]. Overcoming this ecological crisis requires large reductions in carbon dioxide (CO₂) emissions on a global scale, as well as implementation of strategies to adapt to climate change. The energy consumption in buildings, residential or otherwise, is one of the main sources of carbon dioxide in the atmosphere. Therefore, reducing greenhouse gas emissions by optimizing building energy demands is an effective strategy to mitigate the effects of rising temperatures and facilitate the adaptation to climate change. The development of more sustainable and environmentally friendly building materials is an important step towards this direction. A great challenge in construction industry is the reducing of heating and cooling needs in buildings, and the investigation of innovative sustainable design [2]. Particularly, there is an increased interest in biodegradable and renewable biopolymers...
and natural fibers, like Hibiscus sabdariffa fibers, which can improve the properties of composite construction materials when used as additives in the production of concrete [3,4]. The second most used material in construction industry after water is concrete, thus there is a growing interest of sustainable cement solution, like fly-ash and hemp-starch concrete that have been introduced by previous researchers [5,6]. Those building materials have the potential of gradually replacing the traditional ones, such as concrete bricks and various wood, metal and glass products [4].

Polysaccharides such as starch are the most abundant biopolymers in plants. In recent decades, there has been a growing interest in the exploration of biopolymers for the development of biodegradable bioplastics from renewable sources (such as starch derivatives), in order to reduce the environmental pollution caused by synthetic non-renewable sources such as petroleum. Starch is a type of polysaccharide derived from glucose monomers, with \( \alpha-1,4 \) and \( \alpha-1,6 \)-glucans bonds and occurs in plants in the form of granules, which consist mainly of two polysaccharides: amylose (amylose) and amylopectin (amylopectin) with a structural molecule of anhydroglucose units [7]. Having the advantage of being biodegradable at low cost, starch is a promising natural renewable polymer for biomaterial applications in the production of bioplastics and new building materials. Research have developed a simple method for the preparation of corn starch-based films with enhanced tensile properties for various applications like lightweight architectural constructions, biodegradable sandwich panels and packaging [8–11], using native and non-granular corn-based starch [12]. Starch can be extracted from a variety of plant sources such as wheat, rice, corn and potatoes. In its natural granular form, starch consists of a mixture of two polymers: a highly branched polysaccharide—amylopectin and a linear polysaccharide-amylose, the latter being the polymer responsible for the starch gelatinization. Gelatinization can be achieved by mixing dry starch with liquid plasticizers, such as water, glycerol and sorbitol [13–15] at a characteristic value of temperature, typically in the range of about 70 °C to 90 °C. At the start of this procedure, molecules of water are incorporated into the starch network, leading to the relaxation of the hydrogen bonds between polymer chains of starch. Depending on the starch source, most types of starch consist of 20 to 30% amylose [16,17].

Previous work presented the application of native corn starch as a binder in an innovative construction material. Researchers formed a building material by mixing dry corn starch with sand and water and heating the mixture in a microwave and conventional oven. The obtained results indicated a very promising bio-based building material due to its light weight, low cost and eco-friendly nature [18]. Recent studies demonstrated a new technique for the preparation of this starch-based material for commercial applications and purposed eco-friendly coating materials to increase the hydrophobicity of the material structure [19,20]. The purpose of this paper is to go a step further in this research by experimenting on various types of commercial sand and observing their effects on the mechanical properties of the specimens of artificial starch-sandstone materials. The engineering classification, and the physical, structural and durability aspects have been investigated by previous researchers [18–20]; however, there is no published study on the tensile and cyclic compression properties of the study material and how the chemical composition of the sand affects them. One of the main objectives of this research is to investigate how the quality of the sand influences the compressive and tensile strength of the starch-based specimens. The mechanical performance of the studied materials was evaluated based on the water-to-starch ratio and the type of sand. The tensile properties of specimens were measured using the Brazilian Test method. In addition, the behavior of specimens during the cyclic compressive test was examined and evaluated in relation to the mechanical behavior of each type of sand that was used to produce them. This study introduces the application of maize starch in the production of a new biodegradable, sustainable and environmentally friendly building material, that can be used in lightweight architectural structures, with the aim of reducing greenhouse gas emissions from the construction sector and mitigating the effects of climate change.
2. Preparation of Materials and Experimental Details

2.1. Materials

For the purpose of the experiments, commercial corn starch of approximately 23% amylose and 12 wt% moisture content was used. The latter was determined by drying to a constant mass [21, 22]. The corn starch samples were provided by Nestlé Hellas S.A. (Athens, Greece) and they were mixed with four different types of commercial quartz sand provided by Kourasanit (K_Sand), Durostick, (Athens, Greece) (D_Sand), Sigma-Aldrich (St. Louis, MO, USA) (S_Sand) and Laboratory of Advanced Materials and Devices, Department of Physics, Aristotle University of Thessaloniki (Thessaloniki, Greece) (A_Sand).

2.2. Preparation of Hardened Starch-Sandstone Material

The fresh starch-sand composite material was prepared using mixtures of starch and sand at a constant ratio of 1:5 with various contents of water ranged from 8 to 18 wt%, based on the amount of the starch-sand mixture. The corn starch and sand were manually mixed, according to suggestions from previous studies [18–20]. The specimens of the starch-sandstone material were obtained by casting the mixture into molds of cylindrical disks for the Brazilian Test (with diameter: 50 mm and thickness: 25 mm) [23] and into molds for direct compression test (cylindrical specimens with diameter: 27 mm and thickness: 54 mm and cubic specimens 40 × 40 × 40 mm) (Figure 1a) [18, 19]. Molds were prepared using silicon rubber as it is flexible, easy to cast into the proper shape and capable to withstand up to 200 °C without any damage. In addition, it does not absorb microwave radiation during the heating procedure, allowing it to pass through. After the mixture was cast into the silicon rubber molds, the specimens were heated in the microwave (Daewoo Electricals, Manchester, UK, with output power 800 W, model KOR-6C17) for 5 min, and more specifically, in defrost mode for 1.5 min and then at maximum heating power for 3.5 min [18–20].

![Molds for cubic specimens and microwave oven heating method](image)

Figure 1. (a) Molds for cubic specimens and (b) microwave oven heating method by compressing the mold between two Teflon flat plates (fastened together with PTFE screws) to prevent pop up and cracks of specimens at these high temperatures.

Previous studies have developed a simple procedure that required the placement of a surcharge above the specimens during the microwave heating method [18]. Researchers described an improvement of this method, using a preparation technique that mitigated problems like the deformation and cracking of the specimens with the use of two completely flat PTFE plates [19, 20]. According to previous researchers, it is crucial that a weight of 2 kg be placed on the specimens during the heating procedure, in order to prevent the material’s cracks and pop ups that have been observed at these high temperatures. To avoid the extra surcharge, a novel preparation method found in recent literature was also taken into consideration, leading to the addition of three more steps [18]. The specimens were covered with dry sand to absorb the moisture during the heating procedure, and then the mold was placed between two completely flat PTFE plates that were securely fastened together with screws, also made by PTFE (Figure 1b) [19, 20]. To study the effect of
water content on the compressive strength of artificial sandstone, cubic specimens were prepared with water contents ranging from 8% to 18% (6 cubic specimens for each water content). To study the effect of commercial sand on compressive strength, four categories of specimens (six specimens for each water content) were prepared. To study the effect of each commercial sand on the tensile strength of starch-based sandstone, four categories of cylindrical specimens (two types of cylinders) were prepared (twelve for each sand), using the optimal content of water based on the results of the compressive strength test. The samples were sealed in a plastic bag and stored at room temperature (≈23 °C) under controlled conditions of humidity (≈55%).

2.3. Soil Analysis

For the mechanical soil analysis of the different types of sands, a quantitative determination of the particle sizes was performed. The sand samples were dried and the sand was passed through a series of sieves with meshes whose size ranged from 0.125 to 1.0 mm [18–20]. The structural characteristics of the obtained sandstone material were examined by the scanning electron microscopy (SEM) technique using a JSM-840A scanning electron microscope from JEOL, Tokyo, Japan, equipped with an Energy Dispersive Spectroscopy to assess the chemical composition of the sands. Additionally, the micrographs of the sands were obtained using a Zeiss LSM 700 confocal microscope, Wetzlar, Germany).

2.4. Mechanical Properties

The uniaxial compressive strength of the starch-sandstone specimens was evaluated using a M500-50AT (Testometric, Rochdale, UK) universal testing machine which was equipped with a 50 kN load of cell with a loading rate of 10 kN/min. The compression properties of the composite starch-sandstone material were determined according to the NEN-EN 196-1:2016 standard test methods [18–20,24]. Two triplicates of specimens from each mixture were prepared and tested. The results are presented as the average compressive strength (MPa). The tensile strength of the samples was further determined by the indirect method of Brazilian Test, in which a diametrical load is applied over the length of a disk with a ratio of length to diameter (L/D) equal to 0.5 [25–27]. For the Brazilian Test, a servo-controlled INSTRON compression testing machine (type UTM-HYD, 4500 KP_X, Waltham, MA, USA) at a constant strain rate of 8.3 × 10^{-5} was used [25,27,28]. The tensile properties are expressed as the average test results of two triplicates of specimens from each prepared and tested mixture. All specimens were tested at a room temperature of about 22–23 °C.

Cyclic compression tests were conducted with a constant strain rate for the loading and unloading phase and, also, all experiments were performed at ambient temperature. All measurements were performed using a universal testing machine (Testometric, equipped with a 50 kN load cell) with a peak load up to 3.5 kN and with a frequency of 0.01 Hz. The speed of the load cell during the loading and unloading phase was set constant with an exact value of 5 mm/min.

3. Results and Discussion

3.1. Morphology of the Sands

The experimental results of the mechanical soil analysis showed that the granulometric grading of the sand particles influences the compressive strength of the material [18–20]. To study the influence of sand grain size, compressive strength tests were performed on specimens of four different types of sand. As measured above, A_Sand, K_Sand and S_Sand contained particles of size between 0.125 and 0.450 mm. Regarding D_Sand, an inhomogeneous grading of the sand grains was observed, with particle size between 0.25 and 1.0 mm. Samples with sand grain size of about 0.125 to 0.450 mm exhibited better mechanical properties, whereas in the case of D_Sand, the results indicated lower values of compressive strength, in agreement with previous studies. However, elemental analysis
seems to have a significant effect on the strength of the specimens. Figure 2 shows the results of the mechanical soil analysis and the micrographs of the four types of sands.

![Graphs and micrographs](image)

**Figure 2.** Results of the mechanical soil analysis and the micrographs of the four types of (a) K and A_Sand and (b) D and S_Sand.

The probability (PDF) and cumulative (CDF) density functions of the estimated shifted lognormal distribution of the particle size (in μm) of the K, A, D and S types of sand are presented in Figure 2. The curve of the lognormal distribution depends on three factors: the mean, standard deviation and shifting parameter. The mean determines the location of the center of the distribution, the standard deviation determines the height and width of the curve, and the shifting parameter is a measure of the asymmetry and kurtosis of the distribution.

In addition to the size and the shape of the sand particles, the chemical composition of the sand is also expected to have a significant effect on the strength of the specimens. As shown in Figure 3 from the Energy-dispersive X-ray spectroscopy (EDS) analysis, sand types with similar elemental analysis showed similar results to their respective mechanical strength values. An example is the analysis of A_Sand and K_Sand as the sands that gave specimens with the highest values in compressive strength. Elemental analysis of D_Sand showed that in addition to the inhomogeneous grading of its grains, it had also different
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(a) A_SAND

(b) K_SAND

(c) D_SAND

Figure 3. Cont.
3.2. Compression Test Results

The purpose of this research is to determine the best combination of water content and commercial sand type for improved mechanical properties. The specimens of hardened starch-sandstone material obtained from the preparation procedure described in the previous section were macroscopically homogeneous, porous and bulk as illustrated in Figure 4a. Depending on the content of water and baking conditions, the samples may become more brittle, with cracks and reduced strength as shown in Figure 4b. Such observation has been also described elsewhere [18–20].

Water content is very important for the compressive strength of the artificial sandstone specimens. The influence of different levels of water (8–18 wt%) and different types of sand (A_Sand, K_Sand, S_Sand and D_Sand) on compressive properties are presented in Table 1 and Figures 4 and 5. As it is known from previous research [18–20], water content is related to the level of gelatinization of corn starch. It is obvious from the results that the interaction between the gelatinization level of corn starch and the sand type greatly affects the formation of the microstructure of starch-sandstone material and the mechanical properties of the samples. Samples prepared with the same sand type and water content of approximately 12 wt% were associated with better mechanical strength, i.e. compressive strength (Figure 4a,b, Figure 5a,b and Figure 6). The relatively low standard deviations (stddev) of the compressive measurements indicate the homogeneity of the samples. It is important to notice that at water content values above about 18 wt% or below about...
8 wt%, the samples have shown considerable amount of cracks, fragile behavior and low compressive strength.

Table 1. Results from compression test of the effect of sand type on compressive strength of starch-sand composite specimens.

<table>
<thead>
<tr>
<th>Type of Sand</th>
<th>Compressive Stress (MPa)</th>
<th>Stdv (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>D_Sand</td>
<td>21.23</td>
<td>1.24</td>
</tr>
<tr>
<td>S_Sand</td>
<td>26.55</td>
<td>0.95</td>
</tr>
<tr>
<td>K_Sand</td>
<td>28.71</td>
<td>1.27</td>
</tr>
<tr>
<td>A_Sand</td>
<td>30.64</td>
<td>1.97</td>
</tr>
</tbody>
</table>

Figure 5. (a) Cubic specimen of artificial sandstone with K_Sand before compression test and (b) compression test on the starch-based cubic specimen under ultimate load (the illustrated specimen contains 12 wt% water based on the dry starch-sand mixture).

Figure 6. Mechanical properties of starch-sand composites as a function of water content with D, S, K and A sand (with constant sand to starch ratio 5:1).
The experimental results showed that the water content has a great impact on the mechanical properties of the specimens (Figure 5a,b and Figure 6). At very low water content, the amount of water is insufficient for complete gelatinization of the starch resulting in the limited integration of the sand grains in the polymer starch matrix and the low strength of the samples. At high water content, there is too much water not absorbed by the starch, and the high internal pressures that occur at high heating rates (throughout the heating process) usually cause the specimens to deform resulting in reduced strength. The optimal water content corresponds to the best compaction of the material, the minimum ratio of empty spaces interposed between the solid particles, the maximum dry density and the maximum compressive strength of the material.

From Table 1 and Figure 7, it can be concluded that quartz sands A, K and S exhibited better compressive performance than D_Sand. This can be attributed to the similar elemental analysis and particle size distribution of A, K and D sands. The different mechanical behavior of the artificial sandstone samples (with the same water content of 12 wt%) in Figure 7 shows that the type of sand is a key factor in determining the different compressive properties of the sand/corn starch-based specimens.

The presence of A_Sand, K_Sand and S_Sand sand increased both compressive strengths compared to D_Sand. A_Sand provided slightly higher increase than sands K and S. The results from this study also confirmed that the incorporation of A_Sand into the starch matrix increased compressive properties of starch-sandstone samples up to approximately 30.64 MPa. However, K_Sand showed better stability in a wider range of water content. In the case of QS sand, it is important to notice that the higher level of compressive strength, up to approximately 28.71 MPa, remains relatively stable from around 12 wt% up to 15 wt% water content. On the contrary, A_Sand, S_Sand and D_Sand sand exhibited a sharp decrease as the water content increased over 13 wt% water content.

The samples obtained in this study showed a higher increase in compressive strength, as can be clearly seen in Figures 6 and 7, compared to other studies, where the highest value of compressive strength was 26.7 MPa (with identical compression specimens’ dimensions according to the same ASTM standards) [18]. In the case of D_Sand, samples exhibited the lowest mechanical properties, up to 21.23 MPa. As illustrated by Figure 7, S_Sand increased the compressive strength of the specimens up to 26.55 MPa. The best results were obtained with A_Sand and water concentration of 12%. These values can be explained by the different sand qualities and the shape of the sand particles.
3.3. Brazilian Test and Cylinder Compression Test Results

To evaluate the tensile properties of the starch-based sandstone material, the Brazilian Test method was used according to ASTM [25,27,28]. The Brazilian Test is a testing method that allows an indirect inference of the tensile strength test, by measuring the indirect tensile strength. This method is useful when measuring tensile properties for brittle materials that have much higher compressive strength than tensile strength, such as concrete, rocks, coal, and ceramics among others. The Brazilian Test can be considered a diametrical compression test (Figure 8a,b and Figure 9). It was performed using the same machine that was utilized to perform direct compression tests with cylindrical specimens (Figure 10a,b and Figure 11).

Figure 8. (a) Solid disks of artificial sandstone with the four types of sand before Brazilian Test and (b) Brazilian Test on the starch-based flat disk specimen under ultimate load (the illustrated specimen contains A_Sand and 12 wt% water based on the dry starch-sand mixture).

Figure 9. Force-displacement graphs from Brazilian Tests.
Figure 10. (a) Cylindrical specimen of artificial sandstone with D_Sand before compression test and (b) compression test on the starch-based cylindrical specimen under ultimate load (the illustrated specimen contains D_Sand and 12 wt% water based on the dry starch-sand mixture).

Figure 11. Compressive stress-strain curves of cylindrical specimen of artificial sandstone with K, D, S and A_Sand and 12 wt% water contents.

For the Brazilian Test, a flat, circular, solid disk was made with a diameter of about 50 mm, and with thickness approximately equal to the specimen’s radius, the latter with the load concentrated in a pair of antiparallel points as illustrated in Figure 8a,b. This caused a tensile stress in the direction perpendicular to the applied load, proportional to the latter’s size. The stress was concentrated near the geometrical center of the cylinder [29].

Due to the findings of the compressive strength test and according to previous research [19,20,30–33], the material characterized as rock material and Brazilian Test was held according to ASTM Methods E4 [25].

The influence of different types of the sand at the tensile properties of the sandstone samples is illustrated in Figure 9 and Table 2. From the graphs in Figure 9, as well as the values in Table 2, it can be inferred that samples with the same water content of about 12 wt% but of different type of sand produced a variety of different values of tensile strength. On the other hand, and contrary to the compressive test results, it can be concluded that...
samples containing K_Sand had better tensile properties up to 5.31 MPa than those with A_Sand, up to 3.1 MPa. Samples with S_Sand and D_Sand exhibited higher values of tensile strength than those with A_Sand, with specimens containing D_Sand and demonstrating slightly improved tensile strength of about 3.87 MPa, compared to those containing S_Sand (up to 3.55 MPa).

Table 2. Results from compression test of the effect of sand type on compressive strength of starch-sand composite specimens.

<table>
<thead>
<tr>
<th>Type of Sand</th>
<th>Tensile Strength (MPa)</th>
<th>Stdv (MPa)</th>
<th>Compressive Strength (MPa)</th>
<th>Stdv (MPa)</th>
<th>Ratio (Tensile/Compressive)</th>
</tr>
</thead>
<tbody>
<tr>
<td>D_Sand</td>
<td>4.02</td>
<td>0.18</td>
<td>15.8</td>
<td>1.45</td>
<td>1/3.93</td>
</tr>
<tr>
<td>S_Sand</td>
<td>3.97</td>
<td>0.45</td>
<td>18.3</td>
<td>1.01</td>
<td>1/4.6</td>
</tr>
<tr>
<td>K_Sand</td>
<td>5.86</td>
<td>0.83</td>
<td>19.69</td>
<td>1.25</td>
<td>1/3.36</td>
</tr>
<tr>
<td>A_Sand</td>
<td>3.62</td>
<td>0.64</td>
<td>22.24</td>
<td>2.87</td>
<td>1/6.14</td>
</tr>
</tbody>
</table>

The results are illustrated in Figures 9 and 11, as well as in Table 2. The ratio of tensile strength to compressive strength is also presented in Table 2. It is important to notice that the best performance in compressive strength using cylindrical specimen (up to 22.24 MPa) was observed to the specimen which contained A_Sand (72.58% of cubic specimen compressive strength). In the case of the cylindrical specimens with K_Sand, the maximum compressive strength was 19.69 MPa (68.58% of cubic specimen compressive strength). When it comes to cylindrical specimens with S_Sand, compressive strength reached about 18.3 MPa (68.93% of cubic specimen compressive strength). Samples containing S_Sand exhibited slightly better compressive strength values than those containing D_Sand, up to 15.8 MPa (74.42% of cubic specimen compressive strength). In order for the compressive strength results to be compared properly, compressive test was repeated with cylindrical specimens, with diameter equal to the thickness of tensile disk specimen, and height equal to the diameter of the tensile disk specimen (diameter: 25 mm and height: 50 mm) [27–29,34–36] (Figure 8a,b).

From the above results, it can be concluded that the compressive strength of the artificial sandstone starch-based material is three to five times larger than its tensile strength. The ratio of tensile to compressive stress of the studied material is about 0.16–0.29 and it decreases as the compressive strength increases. K_Sand exhibited the closest values between tensile and compressive strength (with ratio of about 0.29) while A_Sand gave the lowest values of ratio of about 0.16. D_Sand and S_Sand exhibited very close values of ratios, of about 0.22 and 0.25, respectively.

3.4. Cyclic Compression

The area within the hysteresis loop is related to the loss energy. For damping materials, a larger hysteresis loop represents higher damping, meaning that it can efficiently reduce the level of vibration. The damping factors can be obtained by the area enclosed by the hysteresis loops. Figure 12a demonstrates the typical hysteresis loops curves of the specimens under compressive vibration at 0.01 Hz with a maximum load of 3.5 kN. The energy loss over a cycle (ΔW), the maximum energy of that cycle (W), as well as the loss factor (n) were calculated in order to measure the material damping of the loading–unloading experiments, as shown in Table 3. A bar chart of the damping change among the specimens is demonstrated in Figure 12b. The antivibration property (denoted as ΔW) of A_Sand is the lowest among all the specimens, leading the lowest value of damping. Furthermore, the antivibration property of K_Sand is increased as compared to A_Sand. The K_Sand demonstrated the highest damping constant n, which is the ratio of ΔW to W, among all the specimens tested under cyclic compression. This indicates faster energy dissipation at particular vibration amplitudes and the system becomes stable with less vibration cycles. Although the ΔW is increased for the S_Sand, the W property was also
increased, leading to a lower loss factor, compared to K_Sand. The highest ΔW hysteresis loop area can be observed for the D_Sand, along with highest W energy, leading to a decrease of their ratio and, in essence, its damping capacity. Therefore, the K_Sand is expected to enhance the ability to transform its kinetic energy to thermal dissipation upon the application of an external force.

![Graph](image)

**Figure 12.** (a) Hysteresis loops and (b) hysteretic damping of the cylindrical specimens of artificial sandstone with K, D, S and A_Sand.
3.5. Scanning Electron Microscopy (SEM) Analysis of the Samples

The morphology of the obtained starch-sand composite samples was examined by the scanning electron microscopy (SEM) technique. Images show a compact morphology of sand grains surrounded by thermoplastic starch (Figure 13a,b). SEM analysis clearly illustrates that the mixing of thermoplastic starch with sand and water resulted in solid starch-based materials with extremely porous structure. The highly porous structure morphology of the samples negatively affected the mechanical property of the obtained material, in agreement with previous publications. The durability and the degradation of the starch-sandstone under wet conditions is the major limitation of the studied material. Previous studies showed that samples prepared with commercial quartz demonstrated a complete degradation within a few days when submerged in water. Researchers have suggested promising methods in order to reduce the hydrophilic performance of the examined material, suggesting several low-cost coating materials have been used in past studies to enhance the porous surfaces from moisture and increase their hydrophobicity [19].

Table 3. Damping constants of the sandstone A, D, S and K_Sand.

<table>
<thead>
<tr>
<th>Type of Sand</th>
<th>Area of Hysteresis Loop (ΔW)</th>
<th>Maximum Energy (W)</th>
<th>Loss Factor (n)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A_Sand</td>
<td>0.0041</td>
<td>0.0123</td>
<td>10.5%</td>
</tr>
<tr>
<td>K_Sand</td>
<td>0.0071</td>
<td>0.0125</td>
<td>18.1%</td>
</tr>
<tr>
<td>S_Sand</td>
<td>0.0099</td>
<td>0.0182</td>
<td>17.3%</td>
</tr>
<tr>
<td>D_Sand</td>
<td>0.0114</td>
<td>0.0208</td>
<td>17.5%</td>
</tr>
</tbody>
</table>

Figure 13. Scanning Electron Microscopy (SEM) images of the structural characteristics of the obtained starch-based solid material at (a) 600 μm and (b) 1 mm.

4. Conclusions

In this research, a series of cubic, cylindrical and disk starch-based artificial sandstone specimens with a starch to sand ratio of 1:5 and various concentrations of water (ranged from 8 to 18 wt% based on the dry starch-sand mixture) were prepared using the microwave heating method. Among the cubic and cylindrical specimens, the best compressive behavior was observed for samples with A_Sand and water concentration of about 12 wt%. The Brazilian Test was employed as the indirect method to determine the tensile strength of specimens with a water concentration of about 12 wt% based on the type of commercial sand they contained, among the four available different types. The highest values of tensile strength were observed in the specimens with K_Sand, the latter also giving the lowest ratio of tensile to compressive strength (1/3.36). Among the samples, the K_Sand specimens exhibited the closest values between tensile and compressive strength. The K_Sand is...
presented with the most improved damping behavior, i.e., the ability to transform its kinetic energy to thermal dissipation upon the application of an external force. Mechanical soil analysis, optical microscopy observations and SEM micrographs coupled with EDS analysis confirmed the effect of the size and morphology of sand grains, as well as the chemical composition of the sand, on the mechanical properties of the samples. In addition, the obtained SEM micrographs of the starch-based artificial sandstone samples confirmed the compact, continuous and highly porous structure. Future work will focus on the investigation of the economic aspects of the studied materials since the low cost of the starch-based sandstone, the fact that it is fully biodegradable, and the low carbon footprint compared to other conventional building materials, make it technically a viable alternative to conventional construction materials. To reach a commercially feasible product, further economic evaluations should be made to ensure that the final product combines low cost and environmental impact, without compromising its mechanical and thermal properties in order to successfully enter the construction market.

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