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Biological Self-Assembled Porous Ceramics as High Temperature Insulation in Steam Transport Pipes

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Abstract

Biological self-assembled porous ceramics could serve as a substitute for asbestos in thermally insulating applications, such as steam transport pipes in coal-fired power plants. To become a viable alternative to asbestos, a biologically self-assembling ceramic would have good thermal stability up to 650°C, have low thermal conductivity, and be nontoxic and light weight. Ball clay was chosen as the base for the ceramic. By adjusting the amounts of water, yeast, salt, and sugar in the slurry, the sample with the lowest density was found, as it would be most likely to yield the highest porosity, and thus lowest thermal conductivity.

1. Introduction

Boilers in coal-fired power plants are often located a considerable distance from steam turbines. As the steam leaves the boiler and is transported towards the turbine, it cools slightly and loses pressure, which reduces the efficiency of the turbine. Temperature has more influence than pressure in terms of efficiency.^[1] To combat this, power plants have traditionally wrapped their steam transport pipes in an asbestos blanket and covered the asbestos with sheet metal.

In the event of a pipe failure (due to creep, corrosion, etc.), the power company must fund an expensive asbestos clean up because of the carcinogenic nature of asbestos.^[2] Due to increased health and safety concerns, asbestos is slowly being phased out and a new insulating material is being sought.

There are many conditions that must be met to produce a full engineering solu-

tion, especially for critical applications, such as power generation. The research conducted here is only a preliminary investigation of a larger problem.

1.1 Design Criteria

The material must be non-toxic, cost effective, easy to install, and lightweight. Due to the high temperatures encountered in a power plant (as much as 600°C), the material must not thermally degrade. In addition to thermal stability, it must be a comparable material to asbestos in terms of thermal conductivity to maintain, if not improve, the efficiency of the system.

1.2 Ceramic Base

Ceramics are known for high maximum operating temperatures and low thermal conductivity. Because of these characteristics, ceramic materials could serve as an asbestos replacement.

Ball clay is a safe, cost effective material that experiences very little shrinkage when fired. It is easy to process and readily available.

Thermal conductivity is difficult to measure, and finding the efficiency of an insulating material is even more complex. One established link is between closed porosity and insulating ability. Since air is a good insulator, but subject to convection currents which cool the surface, having closed porosity forces the air to remain trapped and not aid in convection cooling. Porous ceramics are commonly used in thermal insulation applications.^[3]

1.3 Biological Self-Assembled Ceramics

One form of biological self-assembled ceramic is created by adding yeast to a slurry of ceramic powder, sugar, salt and water. The reaction caused by the biological agent can be qualitatively described as:



The yeast feeds on the sugar and generates alcohol and CO₂ bubbles. To speed up this reaction, salt is added as a catalyst.

An example of a biological self-assembled ceramic is shown in Figure 1. This material was made using kaolin to test the method.

2. Experimental Procedure

To study the feasibility of using biologically generated porous ceramics, the composition with the most beneficial physical properties was examined.

2.1 Developing a Composition

The composition given by the project advisors was a mixture of ball clay, water, sugar, salt, and yeast content. The individual constituents of this initial composition were varied to determine which components had the greatest influence on the density. Table 1 shows the initial composition in terms of a weight fraction and the weight of each constituent per typical sample.

Batches of the initial composition were used to make six samples. The large batch size allowed the material to be homogenized with an electric mixer. Once fully mixed, the batch was divided into six samples. After dividing the samples, a predetermined



Figure 1. Biologically self-assembled kaolin

amount of one of the ingredients from the batch recipe (e.g. salt, water, etc.) was added to each sample to monitor the individual influence of each ingredient on the material. One sample from each batch was unmodified as a control sample. Once poured, the samples were placed under a fume hood at 21°C and allowed to dry.

2.2 Bulk Density

The bulk density is of great importance to this study because it yields the density of the sample excluding open pores. In an insulating application, large open pores are treated as surfaces through which convection can act to transmit heat away from the pipe. Small open pores or closed pores are necessary for an insulating material.

Table 1. Initial composition

Ingredient	Weight Fraction	Weight(g)
Ball Clay	0.475	180
Water	0.359	136
Sugar	0.140	53
Salt	0.00132	3
Yeast	0.00312	7.1

A representative piece of each fired sample was tested for density. The density equation and method are shown in Equation 2 where ρ_s was the density of the ceramic, ρ_w was the density of the water in the container, w_w was the mass of a container filled only with water, w_{cs} was the mass of the sample submersed in water at in the container, and w_s was the mass of the sample.

$$r_s = \frac{\left(\frac{w_w - (w_{cs} - w_s)}{r_w} \right)}{w_s} \quad (2)$$

2.3 Temperature Stability

Temperature stability of the samples was evaluated qualitatively by placing a piece of each of the samples in a box furnace at 650°C for 12 hours in air to note any significant volume changes. It was assumed that after 12 hours, the organic material was completely burned out, and further shrinkage would not occur.

3. Results and Discussion

The amounts of each constituent were varied and summarized in Table 2.

3.1 Control Samples

The control samples from each batch were comparable in consistency and appearance, indicating that the test conditions from batch to batch were similar. This is an important conclusion, since some batches were manufactured on different dates, and an error in a batch would have appeared in the control sample for that batch as well.

3.2 Varying Water Content

Although reaction time was not measured, it varied significantly with water content. Additional water led to faster reaction times and faster drying times. Some of each of the samples with additional water was lost, as the reaction caused the material to overflow the sample containers.

The samples with additional water also produced the samples with the largest pores. Large closed pores are only slightly better than open pores, in that a large pore can contain a substantial convection current.

Table 2. Compositions of samples A-R

Sample	Water (g)	Sugar	Salt (g)	Yeast (g)	PVA (g)
A	136	67	3	7	0
B	136	78	3	7	0
C	136	103	3	7	0
D	136	53	6	7	0
E	136	53	10	7	0
F	136	53	15	7	0
G	236	53	3	7	0
H	176	53	3	7	0
I	156	53	3	7	0
J	146	53	3	7	0
K	136	53	3	7	0
L	136	53	3	7	0
M	136	53	3	14	0
N	136	53	3	21	0
O	136	53	3	28	0
P	136	53	3	7	12.4
Q	136	53	3	7	9.6
R	136	53	3	7	4.9

3.3 Varying Sugar Content

The samples created with additional sugar were very porous, but exhibited differential drying, with the bottom of the samples drying faster than the top.

3.4 Varying Salt Content

Visibly, there was no difference between the control samples and the samples with additional salt. The samples are slightly more fragile when handled than the control samples, which might indicate that excess salt created a defect in the ceramic matrix.

3.5 Varying Biological Agent Content

Yeast was varied by adding yeast packets, each packet weighing 7g. Since the initial composition contained one packet, the three additional test compositions had two, three, and four packets of yeast.

These samples had a slight brownish discoloration, which mostly collected at the bottoms of the sample containers. This could be due to excess yeast starving and sinking into the slurry.

3.6 Varying Binder Content

Poly(vinyl alcohol) (PVA) was added to three samples in hopes of capturing the reaction at its maximum volume change. PVA was chosen solely based on its availability in the laboratory.

The PVA did not mix well with the slurry. It is suspected that the PVA was not water soluble, and thus it sunk through the slurry and settled at the bottom of the sample holders in all three samples.

3.7 Thermal Stability

All samples survived a 12h, 650°C firing with very little shrinkage. Weight loss was significant, as the water evaporated and the organics were lost. This meant that the fired samples were less dense than the unfired samples.

3.8 Densities of Fired Compositions

Table 3 shows the densities of the as-fired samples. The densities did not vary in a predictable fashion. Even those of the control samples K and L varied wildly.

4. Conclusions

The use of biologically self-assembled ceramics might be feasible as steam transport pipe insulation. Since all of the samples survived thermal testing, without significant warping or cracking, they all were eligible for further testing.

Unfortunately, a correlation between any of the single ingredients and the amount of closed porosity could not be drawn. Because of this, further research should be conducted using the initial composition.

5. Future Work

This report is just the initial research on the feasibility of using a biologically self-assembled porous ceramic for insulation material.

5.1 Bonding and Firing

Bonding and firing test should be conducted on the sample of the most ideal composition. This test will involve dipping several small plates of Inconel 740 (a commonly used steam pipe alloy) into a slurry of the ideal composition. The plate will then be fired in a box furnace in air. This test will determine

whether there is any corrosion of the Inconel plate by the material.

Another concern is a partial bonding scenario where the plate partially bonds to the material, but then differences in thermal expansion cause the material to crack

Table 3. Densities of fired compositions

Sample	Density (g/cm ³)
A	6.1 ± 0.05
B	2.6 ± 0.05
C	3.3 ± 0.05
D	4.5 ± 0.05
E	1.6 ± 0.05
F	2.2 ± 0.05
G	3.1 ± 0.05
H	2.2 ± 0.05
I	1.2 ± 0.05
J	2.1 ± 0.05
K	2.3 ± 0.05
L	1.2 ± 0.05
M	1.1 ± 0.05
N	1.4 ± 0.05
O	5.1 ± 0.05
P	3.8 ± 0.05
Q	0.2 ± 0.05
R	1.5 ± 0.05

5.2 Thermal Expansion

Due to the drastic temperature changes in steam pipes, thermal expansion data should be collected before attempting to use any material for insulation. Thermal expansion can be measured with a dilatometer, insuring that there are no unexpected phase changes during heating and cooling.

5.3 Varying Drying Temperature

The time required for the mixture to dry and harden is dependent on the drying temperature. All data collected thus far have been on samples dried in a fume hood at room temperature (21°C). A higher

drying temperature will begin to kill the biological agent; therefore, there is a peak temperature above which yeast begins to die and below which the yeast does not react as quickly.

In the power plant, finding the peak temperature response of the insulation is important to evaluate the feasibility of simply “turning on the power” to dry, harden and fire the porous ceramic.

5.4 Varying Sugar and Biological Agent Content

Since the sugar and yeast are dependent on each other, further testing should include varying sugar and yeast together. It is possible that additional yeast in tests starved, rather than reacting to its full potential.

5.5 Varying Binder

Though the samples in this experiment showed little effect due to an added binder, further research could be directed at trying other binders in different amounts. A proper composition with a binder at the proper drying rate could capture the ceramic at its maximum volume, and thus minimum density.

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