Compressive Behavior of Plaster of Paris Used for Orthopedic Casting and Multiple Infrastructure Applications

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Abstract

Plaster of Paris (POP) has been used based on its ease of mixing, rapid curing, light unit weight, strength and some of the unique properties (thermal and acoustic) in orthopedic casting and multiple construction and repair applications for centuries. Based on these multiple applications, it is important to better characterize the compressive behavior of POP. In this study the POP samples were prepared using water-to-POP ratio of 0.5 and the initial density was 1.68 g/cc. The one day strength of POP was 2.14 MPa and it increased to 4.32 MPa after 7 days of curing under room condition and also the density reduced to 1. g/cc. After 28 days of curing the compressive strength increased to 6.04 MPa after 28 days of curing. The piezoresistive compressive strain at failure for the POP reduced from 0.76% after one day of curing to 0.68% after 28 days of curing. The compressive behavior of the POP was modeled using the Vipulanandan Piezoresisitive p-q Model and it predicted the behavior very well based on the root mean square error (RMSE). Also the changes in compressive strength with curing time were analyzed and modelled using the Vipulanandan Correlation Model.

1. Introduction

In the medical and veterinary fields, cementitious, polymers and composite materials are commonly used as orthopedic cast material [Parmar et al. 2014, Stefanie, et al. 2011, Lewry et al. 1994]. Plaster of Paris (POP) is the traditional cementitious material used for casting. It is considered the most versatile of splinting materials, is completely moldable and can withstand considerable forces [Stefanie, et al. 2011]. One notable downside of this cast is that the hardening process is an exothermic process. In some cases, these exothermic processes can cause temperatures to rise to dangerous levels and cause thermal injury. Other disadvantages include high water permeability and setting times. An important clinical need is to be able to assess the status of the injured tissue beneath the cast in real time, which itself could cause changes in temperature or moisture. Gypsum or partially dehydrated gypsum (Plaster of Paris (POP)) is considered as one of the oldest construction material that has been used for thousands of years around the world. Also Egyptians as well as Romans have used it for plastering walls however not more is known on plaster used after the end of Roman occupation.

Plaster of Paris takes its name from Paris, France, where it was first widely used chemically, surgically and in construction works (Browner et al., 2008). Plaster of Paris is produced by removing the impurities from the mined gypsum and then heating it under controlled conditions to reduce the amount of water of crystallization (Szostakowski, et al., 2017). The increasing concerns related to environmental impacts of manufacturing of Portland cement at very high temperature (1400^{o}C) and the emission of carbon dioxide during the process, resulting in higher cost of manufacturing and also transportation. Hence there is increasing interest in using alternative materials for construction and maintenance.

The availability of POP as a natural gypsum material and also a byproduct from several chemical industries has made it gain momentum during the past few decades around the world.

Plaster of Paris ($2CaSO_4.H_2O$) is calcium sulphate with water. It is prepared by heating gypsum ($CaSO_4.2H_2O$) at 120°C to allow partial dehydration. When mixed with water, it gives out heat and quickly sets to a hard-porous mass within 5 to 15 minutes. The first step is called the setting stage with a slight expansion in volume. The second stage is the hardening stage.

Stage 1: Heating gypsum at 120 ^oC

$$2(CaSO_4{\cdot}2H_2O) \xrightarrow{\Delta} 2\,(CaSO_4{\cdot}\tfrac{1}{2}\,H_2O) + 3\,H_2O \qquad (1)$$

Stage 2: Plaster of Paris mixed with water

$$2(CaSO_4{\cdot}\tfrac{1}{2}\,H_2O) + 3\,H_2O \rightarrow 2\,(CaSO_4.2H_2O) + Heat \qquad (2)$$

So theortrically minimum of 18.6 grams of water is added to 100 grams of POP powder, water to-binder ration of 0.186, to hydrate it into a solid. Based on the applications varying amounts of water-to-POP is used to mix well with the water, control the rheological properties and hardening process.
Because of its light weight, low density, its acceptable Mechanical properties, these new materials are recommended for exploitation in the manufacturing of popular lightweight construction finishing like panels for ceiling or walls and other applications.

2. Objectives

The overall objective was to characterize the compressive behavior of plaster of Paris (POP) material. The specific objectives are as follows:

(i). Test the POP under compressive loading.

(ii). Model the compressive piezoresistive behavior and strength changes with curing time.

At least three samples were tested under each condition to characterize the material behaviors up to 28 days of curing.

3. Materials and Methods

Material Preparation

Commercially available Plaster of Paris (POP) was used. The water-to-plaster binder ratio used was 0.5. The Plaster of Paris slurries were prepared by hand mixing and adding the POP in three stages into the water. After mixing, POP specimens were prepared using cylindrical molds 50 mm in diameter and 100 mm in height. Also four wires were placed in the mold to monitor the electrical resistance changes.

Methods of Testing

Compression Test

The cylindrical specimens (50 mm diameter and 100 mm height) were capped and tested at a predetermined controlled displacement rate of 0.01 mm/min. Compression tests were performed on POP samples after 1 day, 7 days and 28 days of curing using a hydraulic compression machine.

Modeling

Vipulanandan Piezoresistive p-q Model

The Piezoresistivity behavior of the POP with and without carbon fibers was modeled using the Vipulanandan Piezoresistive p-q model (Vipulanandan 2021) and is defined as follows:

$$\sigma = \frac{\sigma_{max}\times\left(\frac{\left(\frac{\Delta\rho}{\rho}\right)}{\left(\frac{\Delta\rho}{\rho}\right)_0}\right)}{q_2+(1-p_2-q_2)\times\left(\frac{\left(\frac{\Delta\rho}{\rho}\right)}{\left(\frac{\Delta\rho}{\rho}\right)_0}\right)+p_2\times\left(\frac{\left(\frac{\Delta\rho}{\rho}\right)}{\left(\frac{\Delta\rho}{\rho}\right)_0}\right)^{\left(\frac{p_2+q_2}{p_2}\right)}} \quad (3)$$

,

where σ_{max} is the maximum stress at failure, $(\Delta\rho/\rho)_0$ is the piezoresistivity of the hardened cast material under the maximum stress, $(\Delta\rho/\rho)$ is the piezoresistive strain at any stress σ and p_2 and q_2 are the model parameters influence by the composition of the material, material properties and testing environment.

4. Results and Discussions

Density

The specific gravity of the POP powder was 2.54 (manufacture's data sheet). The density of the POP samples prepared with water-to-binder ration of 0.5 with and without carbon fibers was 1.68 g/cc at the time of mixing and the initial porosity was 0.56. The specimens were cured under room condition The density was 1.41 g/cc after 7 days of curing and 1.24 g/cc after 28 days of curing, indicating the loss in moisture during curing.

Compressive Stress- Piezoresistive Strain

It is important to verify and quantify the piezoresistive behavior of the smart POP material. The specimens were cured under room condition and the stress- piezoresistive strain responses were non-linear.

1 Day of Curing

The piezoresistive axial strain for the POP was 0.76% at a peak compressive stress of 2.14 MPa after 1 day of curing as summarized in Table 1 and also shown in Figure 1. The secant piezoresistive modulus at peak stress (ratio of failure stress ($□_{f)}$ /failure piezoresistive axial strain ($□□/□□_0)_0$) was 282 MPa. The initial piezoresistive modulus was 329 MPa. The ratio of secant modulus to initial modulus was 0.855 indicating the non-linearity of the stress-piezoresistive strain relationship.

Table 1 Model parameters for the POP after 1 day of curing.

1 Day Piezoresistivity Model						
Material	p_2	q_2	σ_{cmax} (MPa)	$\Delta\rho/\rho_o$ (%)	R^2	RMSE (MPa)
POP	0.12	0.855	2.14	0.76	0.99	0.055

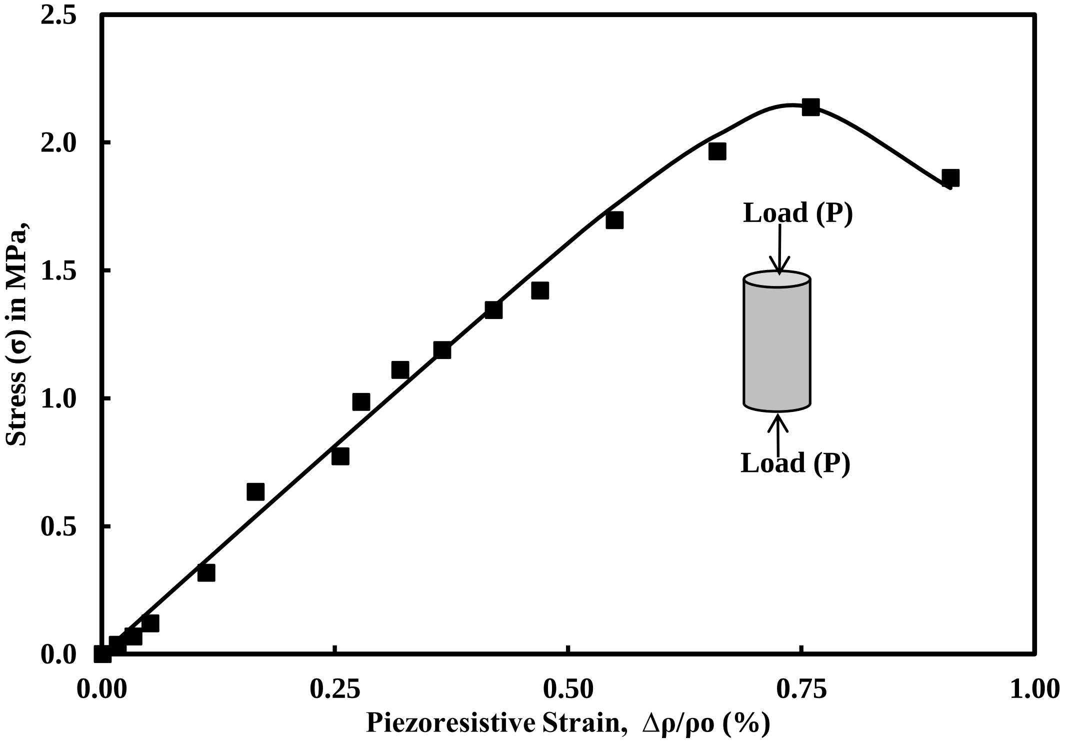

Figure 1 Compressive Behavior of POP Materials After 1 day of Curing.

7 Days of Curing

The compressive piezoresistive axial strain for the POP was 0.72% at the peak compressive stress of 4.32 MPa after 7 days of curing as summarized in Table 2 and shown in Figure 2. The secant piezoresistive modulus at peak stress (ratio of failure stress (□$_{f)}$ /failure piezoresistive axial strain $(\Delta\rho/\Delta\rho_0)_0$) was 600 MPa, over two times higher than the 1 day cured POP. The initial piezoresistive modulus was 642 MPa, about 2 times higher than the 1 day cured POP. The ratio of secant modulus to initial modulus was 0.935 indicating the non-linearity of the stress-piezoresistive strain relationship and it was more linear than the 1 day cured POP.

Vipulanandan Piezoresistive p-q Model: The piezoresistivity of smart POP was modeled using the Vipulanandan piezoresistivity model (Eqn. 9). The model parameter p_2 decreased from 0.12 to 0.065 while the model parameter q_2 increased from 0.855 to 0.935 to after 7 days of curing (Table 2). Vipulanandan piezoresistive p-q model predicted the trend very well as shown in Figure 2. The coefficient of determination (R^2) was 0.99 and the RMSE (root mean square error) was 0.16 MPa as summarized in Table 2.

Table 2 Correlation and model parameters for Piezoresistivity model for smart orthopedic cast material for 7 days of curing.

7 Day Piezoresistivity Model						
Material	p_2	q_2	σ_{cmax} (MPa)	$\Delta\rho/\rho_o$ (%)	R^2	RMSE (MPa)
POP	0.065	0.935	4.32	0.72	0.99	0.16

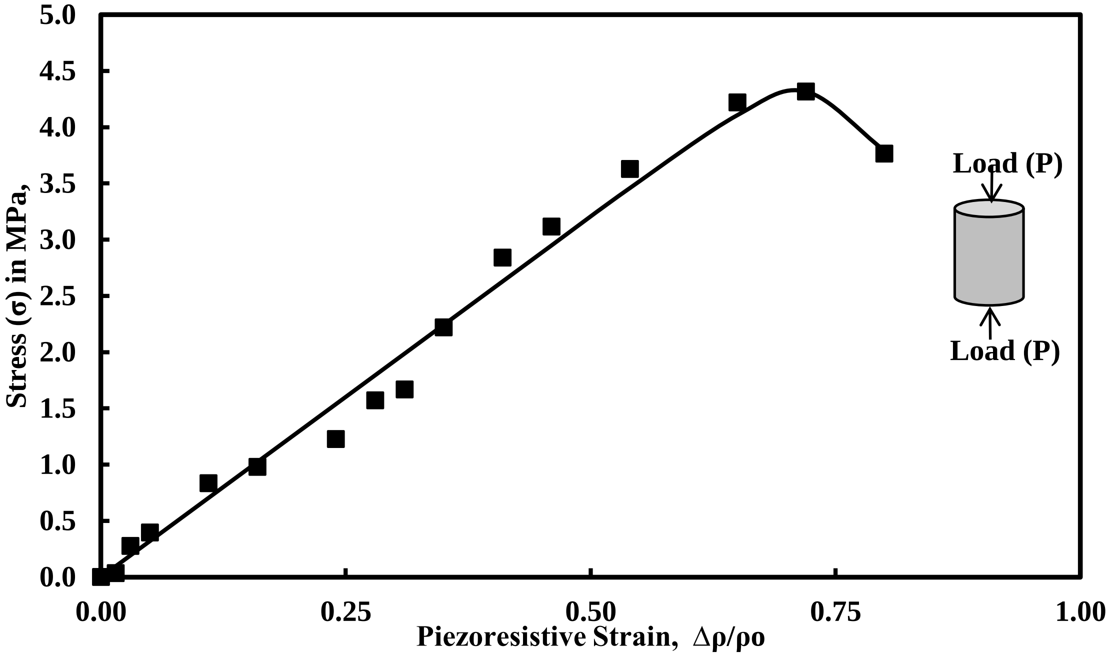

Figure 2 Compressive Behavior of POP after 7 days of curing.

28 Days of Curing

The compressive piezoresistive axial strain for the POP was 0.68% at the peak compressive stress of 6.04 MPa after 28 days of curing as summarized in Table 3 and also shown in Figure 3. The secant piezoresistive modulus at peak stress (ratio of failure stress (□$_f$) /failure piezoresistive axial strain $(\Delta\rho/\Delta\rho_0)_0$) was 888 MPa, over three times higher than the 1 day cured POP. The initial tangent piezoresistive modulus was 945 MPa, about 3 times higher than the 1 day cured POP. The ratio of secant modulus to initial modulus was 0.94 indicating the non-linearity of the stress-piezoresistive strain relationship and it was more linear than the 1 day cured POP.

Vipulanandan Piezoresistive p-q Model: The piezoresistivity of smart POP was modeled using the Vipulanandan piezoresistivity model (Eqn. 9). The model parameter p_2 decreased from 0.053 to 0.091 while the model parameter q_2 varied from 0.908 to 0.946 after 28 days of curing with varying carbon fiber contents (Table 3). Vipulanandan piezoresistive p-q model predicted the piezoresistivity trend very well as shown in Figure 3. The coefficient of determination (R^2) was 0.99 and the RMSE (root mean square error) 0.179 MPa as summarized in Table 3.

Table 3 Model parameters for the POP material after 28 days of curing.

28 Day Piezoresistivity Model						
Orthopedic Cast Material	p_2	q_2	σ_{cmax} (MPa)	$\Delta\rho/\rho_o$ (%)	R^2	RMSE (MPa)
CF = 0%	0.06	0.94	6.04	0.68	0.99	0.179

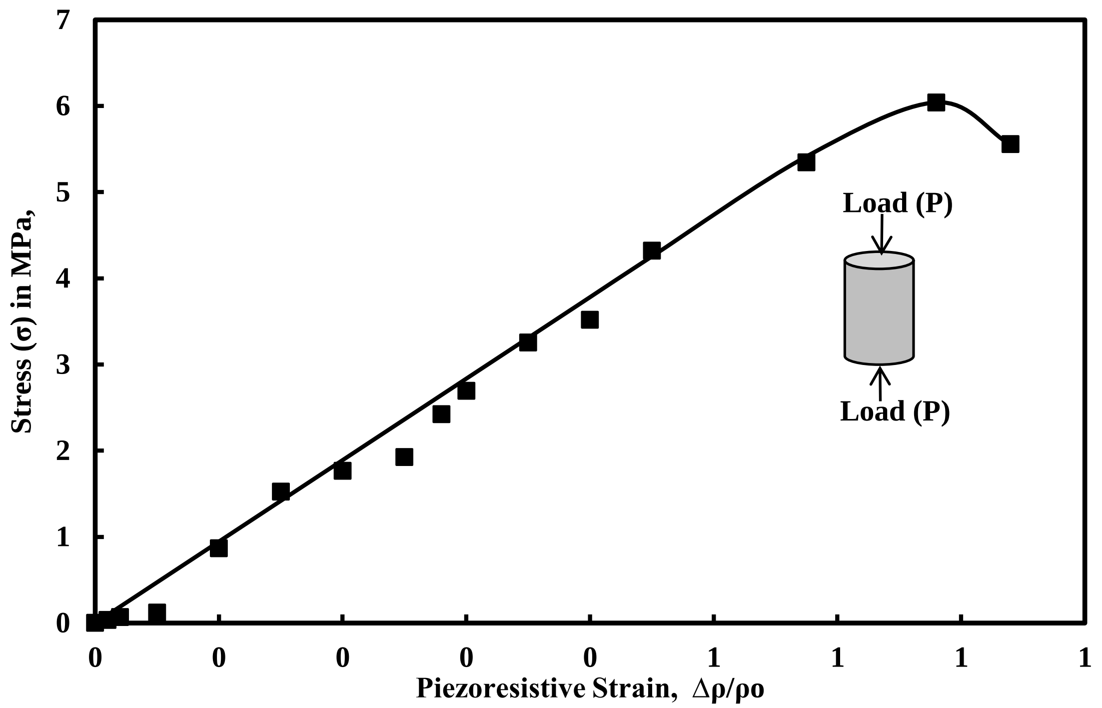

Figure 3 Compressive Behavior of POP Material for 28 days of Curing

Property Changes with Curing Time

It is important to quantify the property (strength, piezoresistive strain at failure) changes with the curing time for the POP with and without carbon fibers. Reviewing the data, Vipulanandan Correlation Model was selected to predict the trends. Vipulanandan Correlation Model is represented as follows:

$$Y = Y_0 + \frac{t}{A+B*t} \qquad (4)$$

Where t is the time and Y is the material property. Parameters Y_0, A and B are the material properties, depends on the compositions and curing environments. The long-term property (Y_∞) can be predicted when the time goes to infinity and can be represented as follows:

$$t \rightarrow \infty \qquad Y_\infty = Y_0 + \frac{1}{B} \qquad (5)$$

Strength

The model parameters Y_o, A and B in Eqn. (9) will be replaced with Y_1, A_1 and B_1 respectively. Also the parameter Y_1 representing the compressive strength at zero curing was zero for all the cases. The variation of compressive strengths with curing time is shown in Figure 4.

The compressive strength after one day of curing was 2.14 MPa and it increased to 4.32 MPa in 7 days, almost doubling (100%) in strength. The 28 day compressive strength was 6.04 MPa and was over 180% higher than the 1 day strength. The model Parameter A_1 was 0.377 day/MPa and the model parameter B_1 was 0.159 MPa^{-1} as summarized in Table 4. Hence the long-term strength predicted by the Model using the Eqn. (5) was 6.29 MPa.

Table 5 Summary of Model Parameters for the Strength of POP

Material	**Parameters**			**RMSE (MPa)**	**R^2**
	σ_o (MPa)	**A1 (days/MPa)**	**B1 $(MPa)^{-1}$**		
POP	**0**	**0.377**	**0.159**	**0.131**	**0.99**

5. Conclusions

Based on the experimental study and analytical modeling of compressive behavior of the plaster of Paris following conclusions are advance:

(1). Compressive strength of the POP increased with the curing time. The density of the POP decreased with the curing time.

(2). The compressive stress –piezoresistive strain relationships were modelled using Vipulanandan Piezoresistive p-q Model.

6. Acknowledgement

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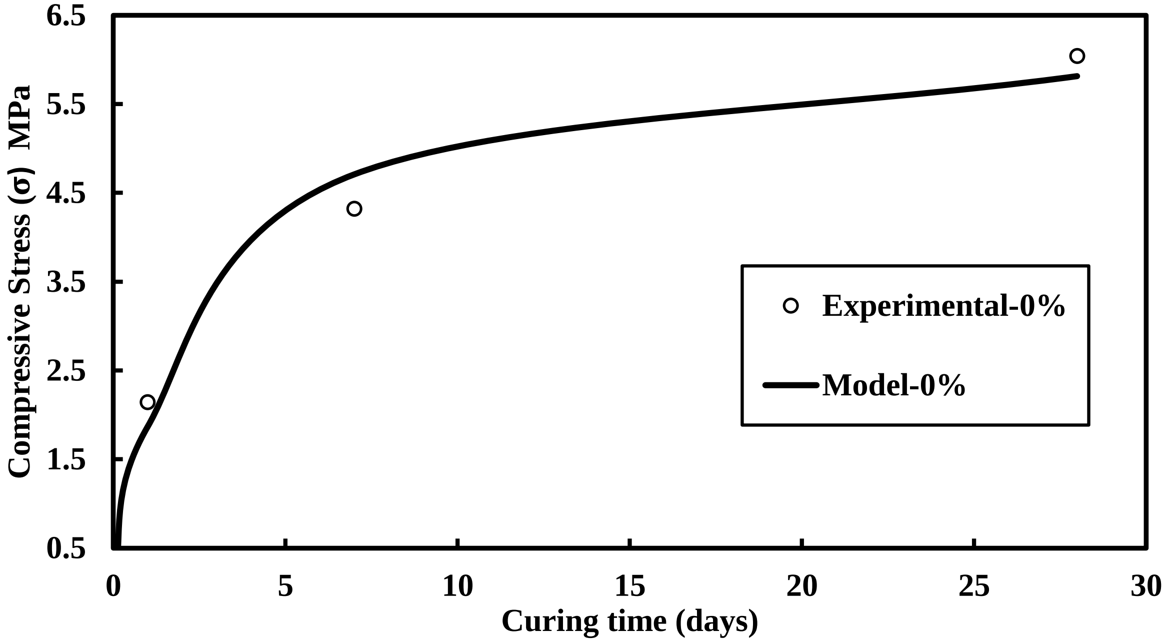

Figure 4 Measured and Predicted Variation of Compressive Strength with Curing Time

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