AUTHOR: Douglas M. Matson[1]

Co-author: Aniruddha S. Nene[2]

Presenter: Doug Matson

Title of Paper: **Use of an insulation-dispersion adobe composite in green building construction**

[1] Associate Professor
Department of Mechanical Engineering
Tufts University, Department of Mechanical Engineering
200 College Avenue, Medford, MA, USA, 02155
Tel: 1-(617)-627-5742
douglas.matson@tufts.edu

[2] Engineer
Camp, Dresser, and McKee
50 Hampshire Street, Cambridge, MA, 02139
Tel: 1-(617)-452-6484
neneas@cdm.com

Abstract:

The Nga Whare Oranga Trust in New Zealand is studying the use of indigenous clay embedded with a dispersed particulate material to fabricate insulation for small-scale structures. The insulation is to serve as a sustainable and inexpensive substitute for commercial fiber products since homeowners may obtain all raw materials onsite and use local labor for processing and installation. The wet clay mixture is molded and dried into adobe bricks, which are then stacked inside wall sections and subsequently covered with wall board cladding. The primary purpose of this adobe is to minimize heat loss to the surroundings although some structural bracing may be realized.

The adobe fabrication process is evaluated with emphasis on the mixing, packing, and drying methods. Two formulations were studied – a local Ohaaki clay with hard indigenous pumice and a commercial Kaolin clay with soft waste polystyrene bead. Experimental verification of the influence of dispersant volume fraction on compressive strength shows that the parallel model of elastic properties of granular composites is the best predictor of adobe performance, with strength decreasing linearly to 0.4 MPa at 50% by volume of the soft dispersant. Thermal conductivity measurements show that the parallel conduction model is not the best predictor of adobe insulation performance as clay properties dominate such that a thermal conductivity of 1.2 W/mK is realized.

1.0 Introduction

The use of sustainable materials in construction is becoming more prevalent, especially in poorer communities (Parra-Saldivar and Batty, 2006). Composite materials are being studied as inexpensive and more effective substitutes for more traditional resources such as pure concrete (Jansen et al., 2001). Our research focuses specifically on the use of composite adobe to build insulation for exterior household wall sections as applied to rural areas of New Zealand where natural deposits of clay and pumice are readily available. The region is also prone to seismic activity and structures must not only be economical but also robust (Minke, 2001). As the use of adobe composite materials is designed to help primarily those in lower economic classes, it is necessary that the resources involved in the brick-making and testing processes are inexpensive, easily accessible, and sustainable. Special emphasis is therefore given to simple approaches to solving problems. This paper discusses the sustainability and insulation properties of adobe mixtures as potential sustainable building materials. Included is a discussion of sustainable practices to fabricate and test candidate adobe mixtures, a presentation of the results of preliminary investigations on strength and insulating capacity of two adobe formulations, and recommendations on the utility of using these materials as insulation substitutes.

Use of adobe as a thermal insulator is typically not recommended (McHenry, 1989). Typical thermal conductivities of conventional adobe approach $k = 1.5$ W/mK (Para-Saldivar and Batty, 2006) making the material more suitable as a thermal mass (to moderate daily swings in temperature) instead of as an insulating layer. It is unclear how the addition of a dispersion of insulating particles will influence this performance.

2.0 Methodology

2.1 Brick Fabrication

In order to standardize testing between brick samples, the clay mixture had to be mixed evenly. In 2005, a Turkish study researched the use of mud bricks reinforced with fibers as a building material. In this case, the dry mud and straw dispersion were first mixed without water. After the straw was evenly dispersed, water was mixed in and the mixture was kneaded to achieve a uniform consistency (Binici et al., 2005). A similar technique was used in our research except that in place of straw, two sustainable dispersants were investigated – one a soft particulate material (polystyrene beads), and the other a hard structural material (pumice). Also in this work, clay was added incrementally to water and mixed evenly using a hand mixer (Allan and Kukacka, 1995).

After the clay mixture was prepared, the brick samples were produced. Two inch by two inch cubical moulds were used to shape the samples into blocks for compression testing and thermal property analysis. The dispersant was mixed into the clay by hand and a vibration table and packing rod were used to settle the clay uniformly throughout the moulds (Turgut and Yesilata, 2008).

Two options were considered for drying. The first was a kiln which allowed for drying to occur swiftly at high temperatures. However this option was rejected because the polystyrene would burn resulting in “the release of [toxic] volatiles if leakages around the exhaust stack exist” (Murray and Liversidge, 1978). Therefore, a Lindberg BlueM model G01330A convection oven set at 50 C was used to better replicate the conditions expected for from sun-drying in the field. Loudon showed that the biggest determinants of thermal conductivity, k, were the moisture and density of a material. It was found that as the density and moisture content increase, so does the conductivity (Loudon, 1979). Therefore, weight vs. time was monitored during the drying process to ensure that it was fully asymptotic before thermal testing of the samples.

2.2 Compression Testing

In the compression phase, bricks were produced with three different initial water contents: 50%, 45%, and 40% by weight. Three sets of compressions trials were conducted for each initial water content value. After a specific mixture was prepared for a given initial water weight, polystyrene beads were added in varying volume increments to each mold to produce a complete batch of seven bricks with different polystyrene bead contents. Here, the percent volume polystyrene refers to the polystyrene content of the final (dry) volume of a brick sample.

A Geocomp LoadTrak II compression consolidation machine was used to test the brick samples had a maximum load of 2000 lbs and a 3 inch stroke. To successfully visualize, record, and analyze the failure of each brick under compression, the strain rate was set relatively low (around 0.07 in/min) and the sampling rate to every 3 seconds. After the plane strain and loading parameters were set, the height and loading surface area of each brick sample were measured and the sample inserted between the platens. Force and crosshead displacement were simultaneously measured and recorded such that stress and strain could be calculated to evaluate the compressive modulus and fracture strength.

2.3 Thermal Testing

For the thermal testing phase, the initial water content of the mixture with respect to weight was 45% for the polystyrene composite. The first sample contained 0% polystyrene. For the second and third bricks, 30 and 60 cm^3 of polystyrene were measured out, which corresponded to dry volume fractions of 0, 0.247, and 0.472, respectively.

In order to simulate conditions anticipated in the field, only simple and sustainable techniques were employed during data collection. Type K thermocouples were baked directly into the bricks at three known positions. A hot plate was then used as the heat source with a granite block of known thermal conductivity serving as a calibration layer to measure the heat flux through the assembly after reaching thermal equilibrium. The granite interface also prevented the polystyrene dispersion from becoming burned due to direct contact with the hot plate. Knowing the flux, the thermal conductivity could be calculated by measuring the height of the bricks and the temperature difference between the top and bottom surfaces assuming one-dimensional steady-state heat transfer.

2.4 Ohaaki and Pumice Samples

The compressive strength of the Ohaaki and pumice composite was tested at three different volume fractions of pumice. The first sample contained pure clay. The second sample had a dry volume fraction pumice of 0.3492. The third sample was pure pumice. In this case, a razor blade was used to shape the sample into a small rectangular piece with a cross-sectional area of 0.82 square inches and a height of 1.13 inches. These samples were subjected to compression testing in the same manner as the polystyrene samples.

For the thermal testing of this composite, bricks with four different dry volume fractions of pumice (0, 0.349, 0.524, and 1) were fabricated. The pure pumice brick was shaped from a sample of fused pumice and was considerably smaller than the other cubical bricks. Instead of baking thermocouples into the bricks, the temperature gradient was calculated from the top and bottom surfaces of the bricks as would be done in the field.

3.0 Results

3.1 Thermal Data

Thermal conductivity measurements yielded values of 1.42, 1.29 and 1.22 W/mK for composites with 0, 0.247 and 0.472 volume fraction polystyrene, respectively. As the amount of polystyrene increased, the thermal conductivity displayed a downward trend as desired. Unfortunately, the rate of decrease was small in magnitude. As a comparison, the literature value for thermal conductivity of polystyrene is 0.13 W/mK (Callister Jr., 2003). For the Ohaaki/pumice composite bricks, the thermal conductivity also showed a downward trend with progressively higher volume fractions of dispersion. Here, conductivity measurements yield values of 1.51 1.49, and 1.23 W/mK for 0, 0.349, and 0.524 volume fraction pumice, respectively. For comparison, the thermal conductivity of pumice is 0.306 W/mK (Binici et al., 2007).

3.2 Compression Data

As expected, the compressive strength decreased as the volume of polystyrene beads increased. Figure 1 shows the average of the compressive strengths across three trials, for each series of initial water weights. These results showed that there is no discernible relation between compressive strength and initial water content.

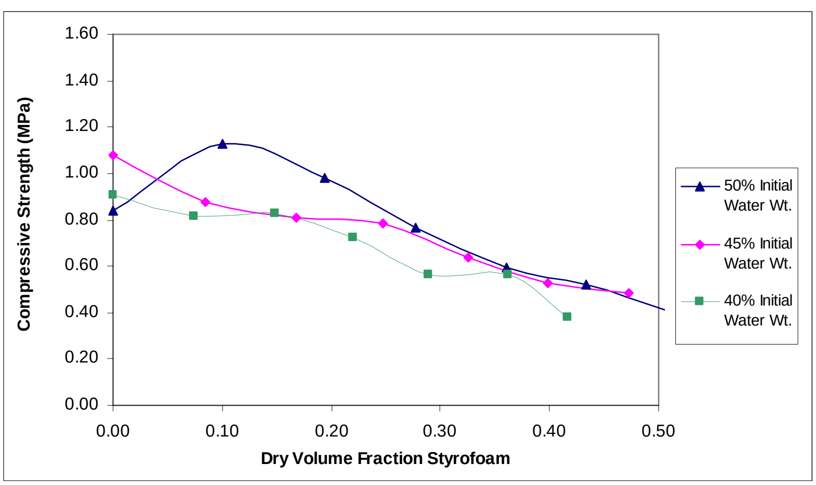

Figure 1: Average strength vs. polystyrene content (separated by water content)

With a limited amount of material, only a few samples could be made from New Zealand clay and pumice. The compressive strength of the pumice samples was 0.51 MPa for pure Ohaaki clay, 1.07 MPa for pure pumice, and 0.32 MPa for a 0.349 volume fraction pumice composite.

4.0 Modelling

In order to understand how changes in composite composition will influence the resulting thermal and mechanical properties, it is important to determine what physical properties are to be measured and how they interact. Once a mathematical model has been validated, the designer can manipulate how the adobe is formulated to obtain optimal properties for an application or predict how changes to the mix will influence performance. In homogeneously mixed clay, the dispersion is scattered randomly throughout the brick's volume. In order to analyze the mechanical and thermal behaviour of a composite material, the randomness of the dispersion can be modelled in two ways: series and parallel. These models assume that a load or a heat flux is applied vertically to the top surface of a brick.

The series model, or Reuss' isostress model, shown below (Hansen, 1958) will be considered first in terms of its implications for heat transfer and then for evaluation of modulus and failure. In this case, the composite brick is modelled as a series of horizontal sections of matrix and dispersion. In Figure 2, the middle image shows a summation of all the matrix sections and the summation of all the dispersant sections yielding a brick with two horizontal sections: one consisting purely of matrix and the other purely of dispersion. This configuration represents the idealized geometry for heat transfer analysis. In terms of thermal behaviour, the flux per unit area is equal for both sections since the cross-sectional of the matrix is equal to the cross-sectional area of the dispersion and thus the overall conductivity is based solely on the relative volume fractions of dispersant, f_d, and matrix, f_m, in combination with the thermal conductivity of each phase, k_d and k_m respectively.

$$k^{-1} = \left(\frac{f_d}{k_d} + \frac{f_m}{k_m}\right) \tag{1}$$

This limit is in practice never reached and less conservative bounding techniques such as the Maxwell limit may often be employed.

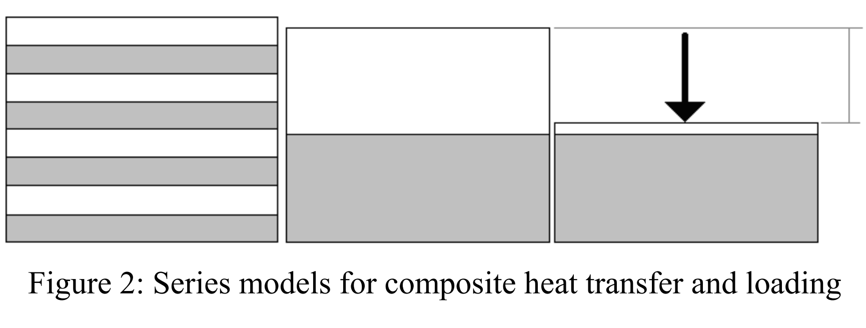

Figure 2: Series models for composite heat transfer and loading

If a downward compressive force is applied to the brick, as shown in the image on the right side of Figure 2, the load is distributed uniformly across the cross-sectional area and the strength of the brick would be controlled by the weaker of the two horizontal sections. Under compression, the brick would assume the shape shown in the right side of the figure. There is no load sharing and the composite fails at whichever yield strength is lower – the matrix or the dispersant. In the case of the polystyrene this will be the dispersant and in the case of the pumice this will be the matrix.

$$\sigma_y = \sigma_d \quad \text{if } \sigma_d < \sigma_m \quad \text{or} \quad \sigma_y = \sigma_m \text{ if } \sigma_d > \sigma_m \qquad (2)$$

In the parallel model, or Voigt's isostrain model, instead of dividing the composite into two individual horizontal sections of different components, the material is now modeled as parallel columns of pure matrix and pure dispersion (Hansen, 1958). The cross-sectional area is now the addition of the total individual cross-sectional areas of the matrix and dispersion columns as seem in Figure 3. The image to left represents the idealized heat transfer model and the right image represents how deformation would proceed with load sharing between the two component phases.

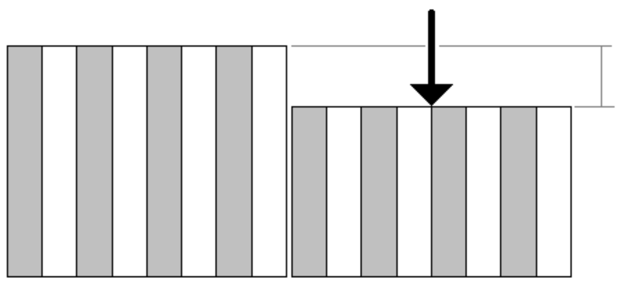

Figure 3: Parallel models for composite heat transfer and loading

Mathematically, in the thermal model the temperature difference in both phases is the same, the flux is additive and the overall thermal conductivity is obtained from the summation of transfer in each phase. Similarly, with load sharing, the overall stress can be evaluated from the sum for each component.

$$k = f_d\, k_d + f_m\, k_m \qquad (3)$$

$$\sigma = f_d \sigma_d + f_m \sigma_m \qquad (4)$$

Equation 4 states that the total stress on the brick is equal to the sum of the yield strengths of the dispersion and matrix multiplied by their respective volume fractions. However, since the matrix and dispersion differ in elastic modulii, either the dispersion or the matrix would reach its yield strength before the other. As such, the instantaneous stresses for every point of strain must be calculated by multiplying the elastic modulus of the matrix and dispersion by the strain.

$$\sigma = E\, \varepsilon \qquad (5)$$

The strain at failure is then identified as the point at which either the matrix or dispersion first reach their yield strength. The stresses for the matrix and dispersion at this failure strain can then be substituted into Equation 4 and then graphed to model the loading behavior. However, the ductility of each material must also be considered in determining the mode of failure. Depending on how brittle a material happens to be, the amount of plastic deformation it sustains before failure will vary significantly. Therefore, the value of strain at the first point of failure must be compared to the strain of failure indicated by the ratio of elastic modulii in order to determine whether ductility or strength controls the overall performance. Thus there are two criteria for failure, yield strength of the weakest component and maximum permissible strain based on the most brittle material.

Figure 4 displays the series and parallel models of thermal behaviour for the polystyrene composite. The measured data for thermal conductivity for this composite is superimposed onto the figure showing that heat transfer through the clay matrix dominates the insulation capacity of the composite. Both models fail to predict actual behaviour and the best estimate of performance is to use properties of the matrix alone. A similar trend was found for the Ohaaki clay / pumice composite. These results show that adobe composites are a poor insulator and perform as inferior candidates for sustainable insulation material.

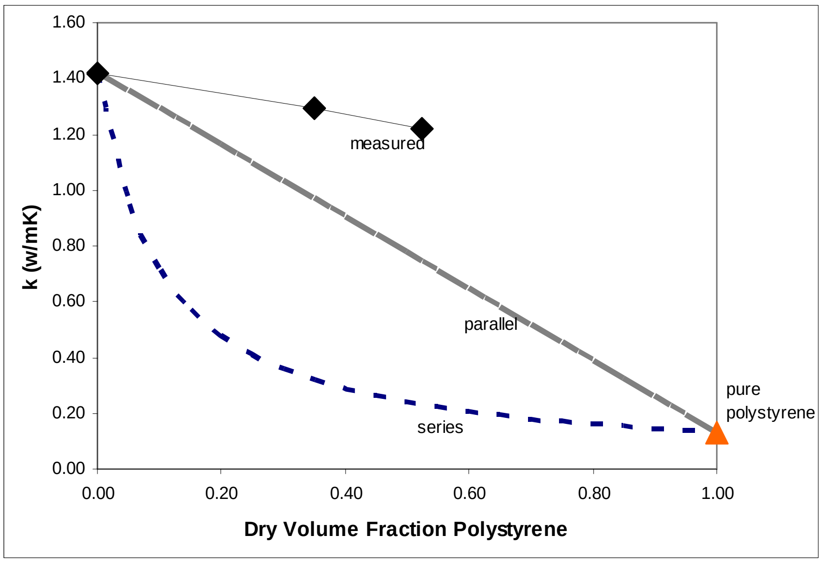

Figure 4: Thermal modeling of polystyrene composite

Compounding this problem, addition of the dispersed phase results in inferior strength for both the soft and hard dispersions. Figure 5 shows the graphs of the series and parallel models for compressive loading behavior of the polystyrene composite bricks. The percent strain of failure dictated by the ratio of elastic modulii for the parallel model is 3.74%. However, the stress-strain behavior observed from the compressive test data indicates that brittle failure first occurred at 3.4% strain. The stresses in the clay and polystyrene at 3.4% strain are 0.85 MPa and 0.03 MPa respectively. These values are substituted into Equation 4 to generate the parallel model for loading. The measured data of average compressive strength is superimposed onto the series and parallel models in Figure 5 with the failure mode being yielding of the polystyrene, as expected for a soft dispersant phase. For these materials, increasing the volume fraction of polystyrene linearly decreases strength according to the parallel load sharing model. By adding material to improve the insulating capacity of the composite, we significantly degrade structural integrity.

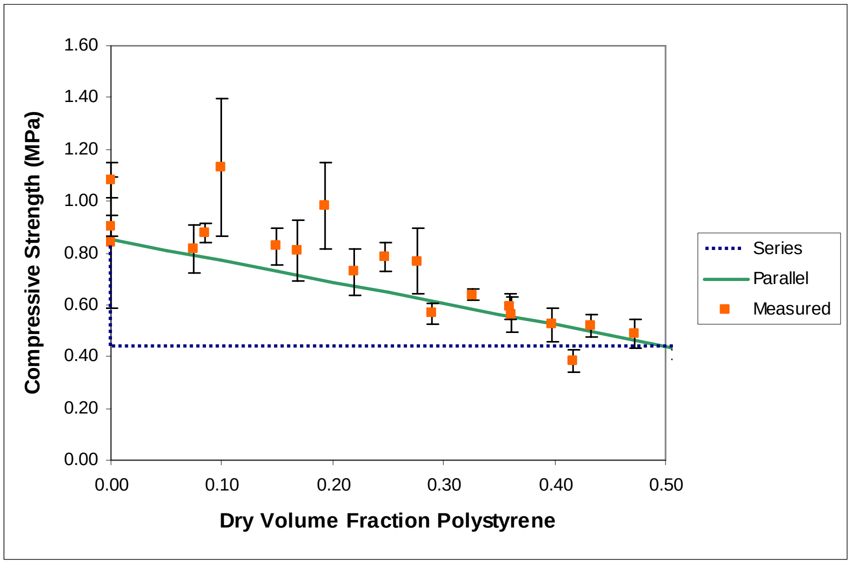

Figure 5: Load sharing behavior of polystyrene composite

Figure 6 displays the strength of the Ohaaki clay /pumice composite during compressive loading for various compositions. In addition to a significant reduction in performance for the dried Ohaaki clay matrix as compared to the Kaolin clay used to make the polystyrene composite formulations, the presence of the hard dispersion changes the failure mechanism from yielding to brittle fracture due to exceeding the strain limit for the clay matrix. The compressive strengths were measured to be 1.07 MPa for pumice and 0.51 MPa for the Ohaaki clay while the elastic modulus was measured to be 13.1 MPa for Pumice and 6.45 MPa for clay. The predicted percent strain at failure dictated by the ratio of elastic modulii is thus 7.9%. However, this is unrealistic for a composite consisting of two brittle materials such as dried clay and solid pumice. Therefore the ductility must be considered. Since the percent strain for clay was determined to be 3.7% (the lower of the two strain limit values), the stresses in the clay and pumice are 0.24 MPa and 0.48 MPa respectively from Equation 5. These values are substituted into Equation 4 to generate the predictions using the parallel model. For a hard dispersion phase, the strength will always be less than either pure constituent due to excessive strain in the matrix.

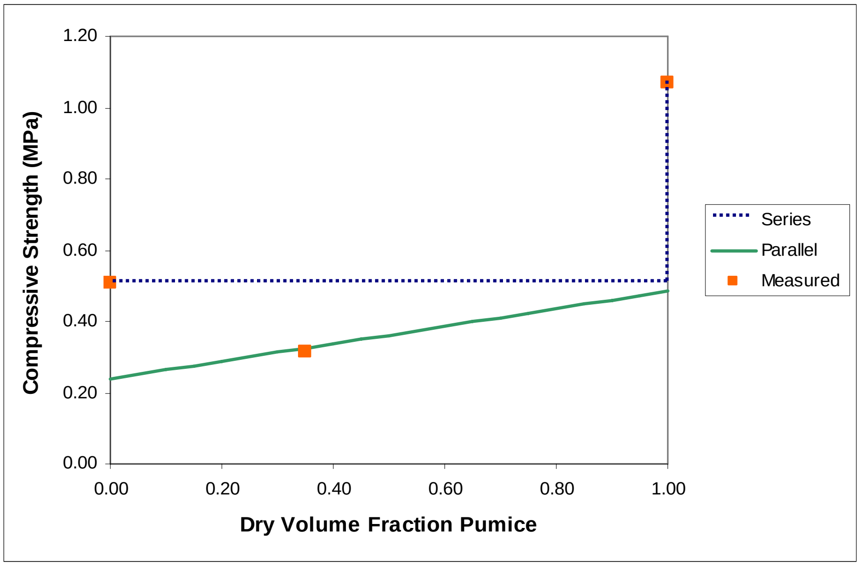

Figure 6. Load sharing behavior of Ohaaki clay / pumice composite

5.0 Discussion

Use of these models as a predictive tool guides the designer in selection of appropriate adobe formulations. By simple measurement of the thermal conductivity, Young's modulus and strain to failure of pure constituents, we are able to predict the performance of any mixture. For heat transfer, the thermal properties of the matrix dominate. In evaluation of an effective insulation material, selection of suitable clay becomes critical. In order to evaluate if specific clays are appropriate, simple thermal conductivity experiments can used to screen materials. The Ohaaki clay used in our experiments is unsuitable for this application.

In an effort to determine if pumice is a good insulating material (Grasser and Minke, 1990), simple heat transfer calculations can be used to determine if additions of pumice into the wall cavity between clapboard and sheetrock, bounded by exterior wall joists, results in significant reduction of the effective thermal conductivity. Here, effective thermal conductivity is defined from one-dimensional heat transfer using a heat balance based on natural convective transport within the cavity where the heat flow Q is calculated based on the free convective heat transfer coefficient h, the exposed wall area A, and the temperature difference between interior and exterior surfaces, ΔT. This is equated to an effective conduction equation based on the temperature difference and the spacing between the heat transfer surfaces, Δx.

$$Q = h\,A\,DT = A\,k_{eff}\,{}^{\Delta T}/_{\Delta x} \qquad (6)$$

Using typical values for air and the Nusselt number correlation for vertical flow inside a cavity (MacGregor, 1969) we obtain a value of $k_{eff} = 0.15$ W/mK. If spherical particulate were poured into the cavity we would expect an average packing density of 65% by volume. Thus, using the rule of mixtures for a "composite" formed of particles in an air "matrix" and using a thermal conductivity for air of $k_{air} = 0.025$ W/mK, we obtain composite thermal conductivities of 0.09 W/mK and 0.21 W/mK for polystyrene and pumice spheres, respectively. Use of polystyrene without clay increases the resistance to heat transfer for the cavity by approximately 30% while use of pumice degrades performance by a similar factor. The pumice proposed for use in our experiments is also unsuitable for this application.

With a poured insulation material, no additional wall bracing is provided. The matrix has no strength. One of the key attributes that the composite wall was to provide was some additional bracing of wall sections during an earthquake. The full potential for application of these adobe mixtures is beyond the scope of this work but load sharing within a composite adobe can now be accurately modeled to predict performance.

For load sharing, the parallel model performs best for both soft and hard dispersed phases in adobe composite. For the soft dispersant, failure of the soft phase dominates with subsequent sequential failure of individual "crush zones". In general, failure did not occur at one specific point for each brick. There were usually multiple instances of the stress dipping suddenly and then recovering almost immediately due to localized yielding of the polystyrene and subsequent localized matrix collapse. This behavior is similar to strain hardening and would continue until a peak stress is reached. At this point, the load would reach a maximum value before catastrophic failure.

For the hard dispersant, failure of the matrix dominates due to exceeding the strain limit for the clay. Due to load sharing, the overall strength is less than for either of the pure materials and thus use of a hard dispersant in adobe is never appropriate given the brittle nature of the matrix material. It would be better to use pure pumice to maximize strength. It is unclear if strength is the most important attribute for an insulation material but increased structural strength is important in areas, such as New Zealand, where seismic activity is common.

In the field, expensive machinery and equipment are not available. However, a simple crush test may be used to measure compressive strength in a sustainable fashion. In the test we designed, bricks are evenly spaced on the floor and a thin 12 inch by 12 inch plastic load support tile is carefully placed on top of it. A large trash barrel of known weight is then centered on the tile. Water is added to the bucket until one of the bricks fail. The peak stress is determined by dividing the weight of the barrel, the plastic plate, and the water by the combined cross-sectional area of the three bricks.

These results are especially significant in that the model validation successfully demonstrates the ability to tailor thermomechanical properties to a specific application in the context of sustainability. The feasibility of using adobe-brick insulation as a sustainable solution can be tested by literally anyone regardless of economic status, but the thermal and structural performance of the adobe will be dominated by the properties of the clay matrix. In the case of the New Zealand clays provided for this study, adobe insulation is not recommended for further study. These results are in general agreement with Australian Alternative Technology Association (ATA) findings where the *Our Home* technology series observed that adobe is a poor insulator but a good thermal mass material. They recommend walls at least 300 mm thick, of comparable thickness to recommendations by Minke (Minke, 2000), which far surpasses the space available between inner wall and cladding for conventional structures.

In contrast to the observations on use of adobe as an insulator, future work on the use of pumice or polystyrene impregnated adobe as a thermal mass seems promising. The insulating performance is better than for pure clay adobe, although not enough to serve purely as an insulating material, and a decrease in thermal conductivity should manifest itself as an increase on the moderating capacity as a thermal mass (Para-Saldivar and Batty, 2006). Our work suggests that maximizing the volume fraction of either pumice or polystyrene enhances performance. In this context, the thermal and structural properties of the adobe significantly improve overall performance of the building and the ability to measure these properties in the field becomes important. The sustainable techniques described in this paper will thus continue to be of interest during green building construction.

6.0 Conclusions

- For both composite formulations, the thermal conductivity of the adobe is dominated by the properties of the clay matrix which results in inferior performance as compared to industrial alternatives.
- Initial water content has no effect on the final compressive strength of a brick.
- For the polystyrene composite bricks, compressive strength decreases as the volume fraction of polystyrene increases. The parallel model with a soft dispersion accurately predicts the linear decrease in compressive strength as a function of polystyrene content.
- For the pumice composite bricks, even with a very limited set of data, the predicted adobe strength is less than for either pure constituent. This is due to the interaction between the hard dispersion and matrix where all of the strain is taken by the matrix causing premature failure of the composite.
- The sustainable crush test serves as an accurate means of determining the compressive strength of a composite material and allows for in-field validation of model predictions.

7.0 Acknowledgements

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