THERMAL PERFORMANCE OF RECYCLED AGGREGATE USING BUILDING ENERGY SIMULATION PROGRAMS

Thomas Nicholas, The University of North Carolina at Charlotte; Tara Cavalline, The University of North Carolina at Charlotte; Dixie Johnson, The University of North Carolina at Charlotte; Morgan Laney, The University of North Carolina at Charlotte

Abstract

As the building industry in the U.S. rapidly expands, the reuse of recycled demolition waste as aggregates is becoming increasingly more common and more urgent. The constant use of raw virgin aggregate is resulting in the depletion of resources, a lack of space for landfills, increasing costs, and heightened levels of environmental impact. The focus of this study was on the effects of using recycled demolition waste aggregates and their corresponding measured thermal properties, including specific heat capacity and thermal conductivity, in masonry mortar applications. The new types of aggregate were analyzed for efficiency and practical utilization in construction in seven locations across the U.S. by embedding the recycled material into the building envelope of a strip mall mercantile build model from the National Renewable Energy Laboratory in the EnergyPlus Building Energy Simulation Program. Thermal efficiency for the utilization of recycled brick masonry aggregate (RBMA) in lightweight masonry construction was modeled for various U.S. climate zones, and its efficiency in each zone was compared to typical steel and masonry construction types. An energy consumption analysis was performed for a baseline steel-framed strip mall. The results were compared to energy-consumption analysis results for: 1) a fully grouted, lightweight masonry wall containing mortar that used normal sand for aggregates (C144 mortar); 2) a fully grouted, lightweight masonry wall that used mortar containing RBMA; and, 3) a fully grouted, lightweight masonry wall that used mortar containing lightweight, expanded slate aggregate. After comparing each of the strip mall construction types, it was determined that the RBMA mortar mixtures performed as well as or better than the C144 mortar mixtures. However, the baseline steel strip mall outperformed the masonry strip mall at several locations. Opportunities for future research in RBMA mortar mixtures exist in a regional analysis, a regional recycled aggregate cost analysis, and a lifecycle cost analysis.

Introduction

Research is being conducted in many areas in order to improve the design and construction of infrastructure and facilities and reduce the environmental impact and energy consumption from the construction phase through the complete service life. A key material used in many facets of the built environment are aggregates. According to Gilpin et al. [1], approximately 2.7 billion metric tons of aggregates per year were used in the U.S. Of those 2.7 billion metric tons of aggregate, pavement accounted for 10-15%, general road construction and maintenance accounted for 20-30%, with the remaining 60-70% going to structural concrete. Recent statistics have indicated that the estimated global consumption of aggregates in construction reached 26 billion tons per year worldwide by 2012 [2], with the demand doubling over the next 20 to 30 years [3]. To alleviate the strain on the environment and on the natural resources associated with this demand for aggregates, recycled aggregates have become an increasingly enticing option for stakeholders. Use of recycled aggregates, including those from construction and demolition (C&D) waste is a promising area for improving the sustainability of our built environment.

C&D waste is defined by the Environmental Protection Agency (EPA) as “the waste material produced in the process of construction, renovation, or demolition of structures,” [4], and can consist of a variety of materials, including crushed concrete, masonry, and pavement [5]. The composition of C&D waste is a function of both the source infrastructure material(s) as well as processing, handling, and stockpiling [6]. C&D waste has successfully been utilized in a number of structural applications [7-9]. However, recycling of C&D waste is not a widely accepted practice, due to stakeholder risk perception and a lack of certainty in the quality of the finished product. Factors such as low tipping fees for landfills also have a direct effect on how the construction industry and municipalities choose to dispose of waste [5], and local market factors can determine whether or not material is available for beneficial reuses in new infrastructure or facilities [10].

A number of studies have been conducted internationally on the use of municipal solid waste and C&D waste as aggregates in various applications, but very little research has been performed in this area in the U.S. Overall, the majority of the research performed on recycled aggregates has been in roadbeds and concrete applications [9, 11, 12]. Although a number of studies exist on reuse of recycled concrete aggregate in structural applications [6, 9, 13-17], less research has been focused on masonry C&D waste as aggregates [6, 8, 9, 18-20]. Relatively little research has been conducted in the area of use of C&D waste as aggregates in mortar and grout applications [21], as will be detailed subsequently.

Before lightweight construction options became available, concrete masonry was the primary material used in building construction. Concrete masonry construction can provide significant benefits to owners, due to the fact that it is energy efficient, products can be locally produced, it includes materials of natural origins with long life expectancies, and can incorporate recycled materials [5]. The thickness and density of concrete masonry construction provide desirable thermal mass characteristics, facilitating the storage of heat. Concrete masonry materials also provide effective thermal storage, due to their high density and specific heat properties, ultimately allowing buildings to have reduced heat and cooling loads, decreased indoor temperature swings, and can shift loads to off-peak hours [22]. Substituting recycled aggregates for raw virgin aggregates in mortar and grout applications could allow buildings constructed with concrete block to be a more sustainable option than conventional masonry construction.

Many types of recycled materials have been studied for use in concrete and concrete masonry applications, but very few have been studied for reuse in concrete masonry mortar and grout [21]. Those that have been studied often have sufficient structural strength and are sustainable substitutes for natural sand mortars. Ledesma et al. [23] studied the use of fine recycled aggregate from concrete masonry waste. The recycled concrete masonry aggregate was obtained from a recycling plant that crushed and sieved, and reinforcing steel was removed from the aggregates before distribution. It was found that up to 40% of the natural sand could be replaced with the fine recycled aggregate; however, there were some negative effects. The fine recycled aggregate mortars stayed wet for a longer period of time. This was due to the inability of water to evaporate from the mortar. The final results indicated that there was no difference in structural strength between the natural sand mortar and the fine recycled aggregate.

In another study [24], the authors analyzed 100% replacement of the natural sand in the mortar mix with demolished houses. The demolition waste aggregate obtained from the houses consisted of ceramic, mortar, and concrete masonry. It was proven through testing that the recycled mortar variations performed as well as the natural sand mortars and often improved the mortar properties. Those same authors stated that "this improvement was due to both the adequate size grading distribution of the recycled aggregates and the low quality of natural aggregates located in Havana, Cuba." Despite the low quality of the natural aggregates, a more environmentally conscious substitute was found. In another study by Nicholas et al. [21], the authors demonstrated the compressive suitability of several masonry mortars that included recycled aggregates as well as C&D waste.

Thermal performance testing of masonry materials is often limited to measured properties of specific materials and conventional wall assemblies. ACI 122R-12 provides guidance on the thermal properties of concrete and masonry materials, including lightweight concrete, mortar, and brick [25]. Other published data in ACI 122-R12 have been prepared in order to provide thermal resistance values, thermal mass values, thermal lag values, and supporting computational methodologies for several of types of conventional masonry wall systems [25]. Tatro [26] provided a review of thermal properties for many materials potentially comprising recycled aggregates in ASTM STP 169D. However, although design values and computational guidance are presented in ACI 122 and ASTM STP 169D, values for recycled materials, often more porous than conventional materials due to the influence of adhered mortar [9], are not specifically provided. Overall, a review of the literature indicates that, by replacing the conventional aggregates used in mortar and grout applications, concrete masonry could be an effective option in sustainable building construction for reasons associated with both beneficial reuse and building energy savings. However, more research is needed, particularly in the building energy area, to validate the limited information available to support this potential recycling use.

Methodology

EnergyPlus is the U.S. Department of Energy's (DOE) robust building energy simulation program (BESP). EnergyPlus was selected for a BESP investigation, due to its ability to comprehensively provide energy analyses and thermal load simulations [27]. Based on a building's physical characteristics, EnergyPlus can calculate heating and cooling loads necessary to maintain ideal thermal control points, conditions through a secondary HVAC system and coil loads, and the energy demands of primary equipment. EnergyPlus models heating, cooling, lighting, ventilation, miscellaneous energy flows, and water use [27]. Another important feature of the program is its ability to factor in weather conditions. Weather data inputs include location, data source, latitude, longitude, time zone, elevation, peak heating and cooling design conditions, holidays, daylight savings periods, as well as typical and extreme periods. For the purposes of this current project, the OpenStudio Application Suite plug-in for Google SketchUp was used. OpenStudio Application Suite was designed by the National Renewable Energy Laboratory (NREL) and was programmed around EnergyPlus in order to provide a supporting GUI interface for whole-building energy modeling simulations [28].

A standard U.S. DOE strip mall model was used to analyze the thermal performance of recycled aggregates in mortar applications in concrete masonry construction. To date, there are six mortar mix designs that have been tested for adequate compressive strength. Testing the compressive strength before obtaining thermal data ensured that the mix designs were adequate for structural use. The six types of aggregates used in the mortar mix designs were C144 (reference sand), expanded slate, DBS (demolition brick sand), DB2, DB3, and DB4. The DBS aggregates had bonding complications during prism testing, due to particle elongation preventing prescribed mortar joint height. As a result, a new DBS mortar mix was created and DB4 was selected due to its strength being the highest of the series.

Two mortar mixtures, C144 and DBS, were tested for thermal performance in Miami, FL, and Phoenix, AZ. Thermal performance testing included specific heat capacity and thermal conductivity. Of the two mortar mixtures, only the most adequate mixtures were selected to replace the C144 fine aggregate. Adequate recycled aggregate mortar models were considered to be models that performed as well as or better than the lightweight and normal-weight C144 mortar models. The U.S. DOE developed a database of sixteen commercial reference buildings across the U.S., which represent all U.S. climate zones and approximately 70% of the commercial building stock [29]. The reference model strip mall investigated in this study was a U.S. DOE benchmark strip mall new construction mercantile building. Figure 1 shows benchmark model proportions and store layout.

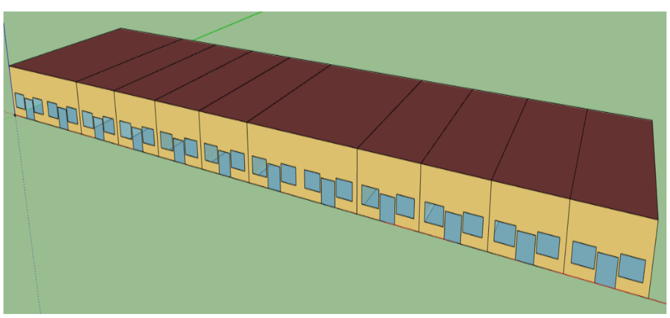

Figure 1. Solid DOE Benchmark Model—Exterior View

The building form required was a single story with an aspect ratio of 4.0 to 1.0 that housed ten stores with a total of 22,500 ft^2 (2090 m^2); the floor-to-ceiling height was 17 ft (5.18m), and it had a glazing fraction of 0.11 [29]. The south-facing wall was the only glazed wall in the strip mall model, including glass doors and windows. The north-facing wall had typical exterior doors for rear store access. Building envelope construction for the concrete masonry strip mall models included fully grouted concrete masonry walls, a built-up flat roof with insulation above deck, and a slab-on-grade floor. The building envelope construction complied with ASHRAE Standard 90.1-2004. Roof construction included a typical built-up roof with a roof membrane, non-resolution roof insulation, and metal decking. Creating a concrete masonry reference model in EnergyPlus using the strip mall reference model was the first step in inserting the recycled aggregate mortar materials. By creating a concrete masonry model based on the DOE reference model, accurate energy use values were generated.

The building envelope had to be changed from steel-framed to concrete-masonry with the EnergyPlus IDF Editor. The concrete-masonry material data were obtained from a predefined EnergyPlus IDF file with building materials from the ASHRAE 2005 Handbook—Fundamentals. The reference building exterior envelope from exterior to interior consisted of wood siding, steel-frame non-residential wall insulation, and ½-inch gypsum. Concrete masonry building envelope construction from exterior to interior consisted of 1 inch of stucco, 8-inch concrete block (lightweight and normal weight with C144 mortar), and ½-inch gypsum. A building envelope was created for lightweight and normal-weight concrete masonry construction using C144 mortar. The thermal performance data gathered for specific heat capacity and thermal conductivity for each mortar mix design were entered into an EnergyPlus strip mall model and compared to a typical U.S. benchmark model. A data-based analysis was then performed between the seven models and a conclusion was made based on whether the recycled aggregates used in the mortar mix design were comparable to those of virgin aggregates. The data analysis determined whether or not recycled aggregates are a more energy efficient option than raw virgin aggregates.

For this current investigation, a building energy simulation was performed in two of the eight climate zones across the U.S. The two building simulations were performed in Miami, FL, (Zone 1A) and Phoenix, AZ, (Zone 2B). These locations were recommended for energy simulation programs by the DOE, due to the overwhelming amount of options at these locations [30].

Results

The performance of both the lightweight model and the normal-weight model were investigated with recycled brick masonry aggregate. Overall, building energy simulations were performed for the DOE reference model, lightweight C144 model, lightweight RBMA model, normal-weight C144 model, and normal-weight RBMA model. After the reference strip mall model was validated against results provided by the DOE, the fully grouted lightweight and normal-weight concrete masonry with C144 mortar building envelopes were substituted for the basic steel-frame envelope.

Miami, FL, is classified as Zone 1A (hot-humid) by the IECC climate zone maps. Hot-humid is defined by the DOE as "a region that receives more than 20 inches (50 cm) of annual precipitation," (U.S. DOE, 2010). Another required condition is that the temperature must be greater than 67°F (19.5°C) or higher for 3000 or more hours during the warmest six consecutive months of the year, or the temperature must remain above 73°F (23°C) for 1500 or more hours during the warmest six consecutive months of the year. Figures 2-4 show the annual percentage of energy consumption by category for the reference strip mall model, lightweight C144 concrete masonry model, and the normal-weight C144 concrete masonry model, respectively. Interior lighting was the largest consumer of energy for all three models. The only variances were in the heating (natural gas), cooling, and fan usage.

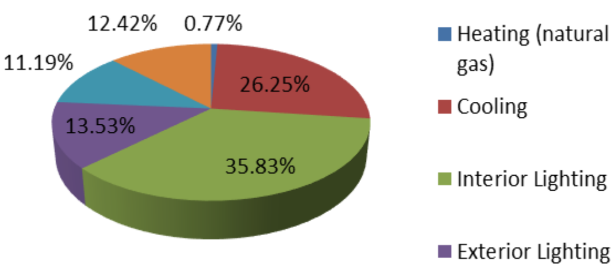

Figure 2. Miami, FL, Strip Mall DOE Reference Model Annual Energy Consumption by End-Use

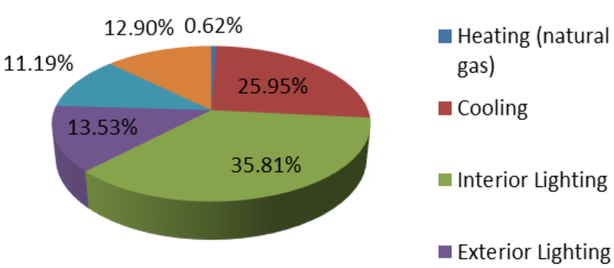

Figure 3. Miami, FL, Strip Mall Lightweight C144 Concrete Masonry Model Annual Energy Consumption by End-Use

Figures 5 and 6 show the end-use energy consumption for lightweight RBMA and normal-weight RBMA mortar models. As with the baseline models for Miami, the main source of end-use energy consumption was the interior lighting. Slight variations in heating (natural gas), cooling, and fan energy usage can be observed.

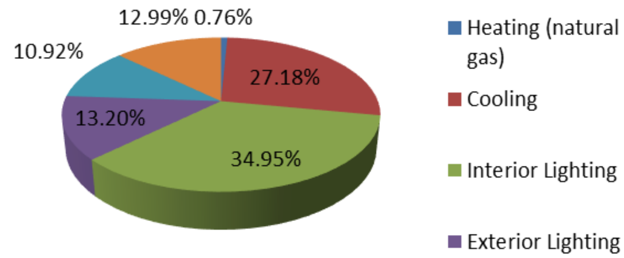

Figure 4. Miami, FL, Strip Mall Normal-Weight C144 Concrete Masonry Model Annual Energy Consumption by End-Use

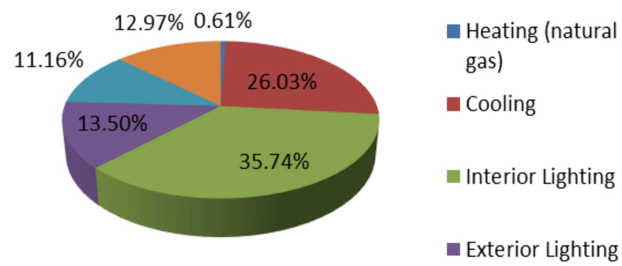

Figure 5. Miami, FL, Strip Mall Lightweight Concrete Masonry Model with RBMA Mortar Annual Energy Consumption by End-Use

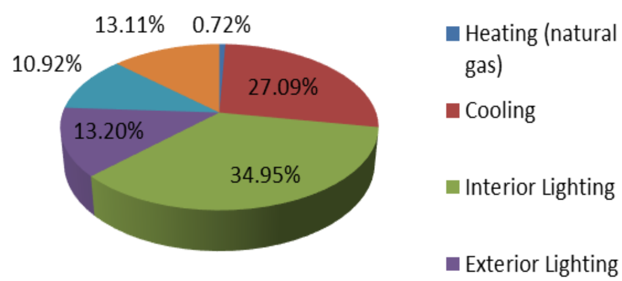

Figure 6. Miami, FL, Strip Mall Normal-Weight Concrete Masonry Model with RBMA Mortar Annual Energy Consumption by End-Use

An energy efficiency decrease of 0.04% for the lightweight C144 model was the most notable change in percent difference between the three lightweight models and the DOE reference model. The energy usage for the lightweight C144 model had an energy efficiency increase of 19.83% for heating (natural gas), an increase of 1.10% for cooling, and a 3.90% decrease for fans. Despite the large increase in heating efficiency, the total efficiency did not increase very much. This was due to the heating only accounting for a total of 0.62% of the entire end-use energy consumption. The lightweight RBMA models decreased in energy efficiency by 0.26% and 0.19%, respectively. Normal-weight models varied little from one another in the total amount of energy consumption. The normal-weight C144 and RBMA models both decreased 2.50% in energy efficiency. Overall, heating (natural gas) increased 4.96%, cooling decreased 5.71%, and fan usage decreased 8.14% in energy efficiency, compared to the DOE reference model. Any of the lightweight models would be a suitable replacement for the DOE steel-frame reference model; however, the best performance was the lightweight C144 model.

An hourly heating and cooling analysis was performed in EnergyPlus for heating and cooling usage over peak temperature weeks for winter and summer. The heating and cooling hourly analyses were performed separately for a comparison of the lightweight models to the DOE reference model results, and the normal-weight models to the DOE reference model results. Hourly data were then combined to report total energy use for the two critical weeks. Due to the hot-humid climate in Miami, heat was only used for a few hours during the coldest week of the year. The use of heat between the lightweight C144 model and the lightweight recycled aggregate mortar models remained consistent with the number of hours the heat operated. The heat operated for a total of fifteen hours from January 1st to January 8th for the lightweight models. Even though the lightweight models operated the same number of hours, the DOE reference model consumed a total of 2.065 GJ, which was higher than any of the lightweight models. The lightweight C144 and lightweight RBMA models consumed 2.013 GJ and 2.021 GJ. A 2.52% increase in energy efficiency was experienced between the lightweight C144 model and the DOE reference model. The RBMA lightweight model experienced an increase in energy efficiency of 2.11%.

The normal-weight concrete masonry models performed differently than the lightweight concrete masonry models. The heat operated for a total of 21 hours over eight days, in contrast to the 15 hours over eight days for the DOE reference model and the lightweight models. This created a large difference in the amount of energy consumed through the peak winter week. All of the normal-weight model hourly consumption results were roughly around the same. For the normal-weight C144 model, 2.495 GJ were consumed and 2.431 GJ were consumed for the normal-weight RBMA model. These values are approximately 0.400 GJ greater than the DOE reference model. A 20.82% decrease in energy efficiency was seen from the DOE reference model to the normal-weight C144 model. Even though the normal-weight C144 model performed poorly, the normal-weight RBMA model performed slightly better. The energy efficiency decreased by 17.71% for the normal-weight RBMA model. Based on the analyses on heating energy consumption between the lightweight, normal-weight, and DOE reference models, the normal-weight models performed poorly. The lightweight models consumed less energy than the DOE reference model.

Due to the hot-humid climate in Miami, cooling systems were running for the majority of the day during the warmest month of the year. The lightweight C144 model and the lightweight recycled aggregate mortar models remained consistent with the amount of energy used for cooling and the number of hours the cooling system was operating. The lightweight models consumed 10.637 GJ for the C144 model and 10.705 GJ for the RBMA model. Cooling energy consumption for the DOE reference model was only 10.560 GJ and operated for a total of 109 hours from January 1st through January 8th. Like the DOE reference model, the lightweight concrete masonry models' cooling systems also ran for a total of 109 hours over the same time period. In comparison to the DOE reference model, the lightweight C144 and lightweight RBMA models decreased in energy efficiency by 0.73%, 1.38%, and 1.17%, respectively. Of the two lightweight concrete masonry models, the C144 model performed the best. The normal-weight models consumed approximately 0.5 GJ more while cooling than the lightweight models. Half a gigajoule means that there is a larger energy gap between the DOE reference model and the normal-weight models. The normal-weight models consumed 11.384 GJ for the C144 model and 11.370 GJ for the RBMA model.

Even though the weekly sum of the cooling energy consumption was higher for the normal-weight models, the number of hours required to cool the facility remained at 109 hours. A 7.80% decrease in energy efficiency was seen from the DOE reference model to the normal-weight C144 model. The normal-weight expanded slate and RBMA models also decreased in energy consumption, but by slightly less at 7.67% and 7.60%. Both the lightweight models and the normal-weight models exceeded the energy usage of the DOE reference model for cooling. Although the energy consumption was greater, it only exceeded the DOE reference model by a very small amount. Miami experiences intense summer temperatures and requires a large amount of energy for cooling. The normal-weight models consumed more energy, but the normal-weight recycled aggregated variations outperformed the normal-weight C144 model. The DOE reference model or lightweight concrete masonry models would be a suitable energy efficient choice, based on these results.

An energy consumption analysis was performed for fan usage during the winter and summer. Fan energy consumption peak weeks are from January 1st to January 8th, and July 1st to July 8th. During the winter, fan energy consumption was much higher than the fan energy consumption during the summer. The percent difference in the fan energy consumption during summer versus winter was consistently 3.60%. Interestingly, the fan energy consumption was consistent during the winter and summer peak weeks. Phoenix was classified by the IECC climate map as Zone 2B, hot-dry. Mix-humid climate conditions are defined as a region where the monthly outdoor temperature remains greater than 45°F (7°C) year round with less than 20 inches (50 cm) of annual precipitation (U.S. DOE 2011). These conditions are applicable to IECC zones 2 and 3.

Figures 7-9 show the percentages of annual energy consumption by end-use for the DOE reference, lightweight concrete masonry, and normal-weight concrete masonry simulations in Phoenix. Ranging from 31.88% (normal weight) to 33.97% (lightweight) energy consumption, lighting consumed the most energy. Cooling consumed the second highest amount of energy, ranging from 18.46% (lightweight) to 20.09% (normal weight). A hot-dry climate requires more cooling than other climate classifications.

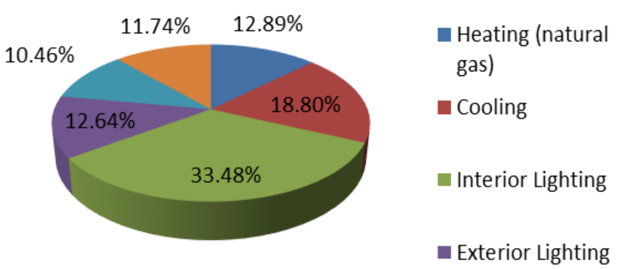

Figure 7. Phoenix, AZ, Strip Mall DOE Reference Model Annual Energy Consumption by End-Use

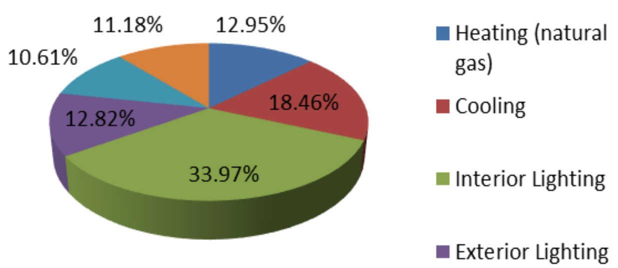

Figure 8. Phoenix, AZ, Strip Mall Lightweight C144 Concrete Masonry Model Annual Energy Consumption by End-Use

Figures 10 and 11 shows annual end-use energy for the lightweight RBMA and normal-weight RBMA mortar models. For the lightweight and normal-weight models, the main consumers of energy were interior lighting and cooling. More energy was required for cooling, due to the warmer climactic conditions in Phoenix. Interior lighting for the lightweight models consumed nearly a third of the overall annual energy consumption. The lightweight C144 model consumed 33.97%, while the lightweight models consumed 33.87% and 33.93%, respectively. The second largest consumer of the annual end-use energy was cooling. Cooling increased from the lightweight C144 model to the lightweight recycled aggregate mortar models. The lightweight C144 model cooling consumption was equal to 18.46% and increased to 18.58% for the lightweight RBMA model. Like the cooling energy consumption, the fan energy consumption also increased from the lightweight C144 model to the lightweight recycled aggregate mortar models. Fans consumed 11.18% of the energy for the lightweight C144 model, and 11.26% was consumed for the lightweight RBMA model. Heating was the last main consumer of annual end-use energy for the lightweight models. Energy consumption for heating decreased from the lightweight C144 model to the lightweight recycled aggregate mortar models. The lightweight C144 model energy consumption was equal to 12.95%, and the recycled aggregate mortar models consumed 12.93% (RBMA) and 12.90% (expanded slate).

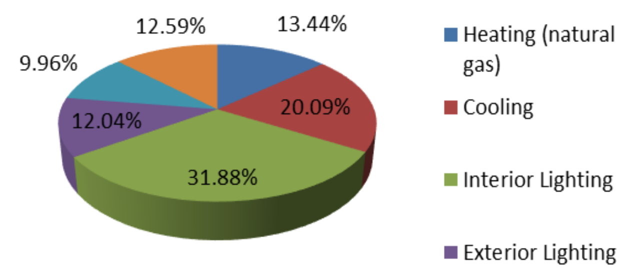

Figure 9. Phoenix, AZ, Strip Mall Normal-Weight C144 Concrete Masonry Model Annual Energy Consumption by End-Use

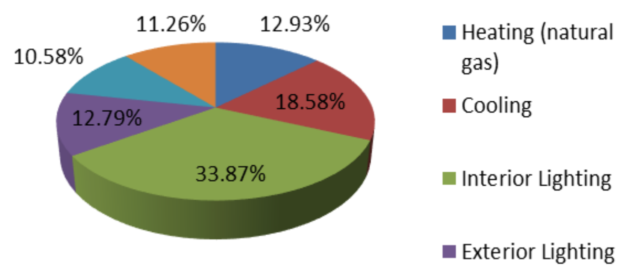

Figure 10. Phoenix, AZ, Strip Mall Lightweight Concrete Masonry Model with RBMA Mortar Annual Energy Consumption by End-Use

The Phoenix normal-weight models were similar to the lightweight models in that the interior lighting also consumed about a third of the annual end-use energy consumption. In contrast, the interior lighting consumption for the normal-weight models decreased from the C144 model to the recycled aggregate mortar models. The normal-weight

C144, RBMA, and expanded-slate models were equal at 31.88%, 32.04%, and 32.08%, respectively. The second largest consumer of end-use energy was cooling. Similar to the lightweight models, the normal-weight model cooling consumption decreased from the normal-weight C144 model to the recycled aggregate mortar models. The normal-weight C144 model consumed 20.09%, and 20.04% was consumed by the normal-weight RBMA model. Unlike the lightweight models, the next largest consumer of energy for the normal-weight models was heating. The energy consumption increased from 13.44% for the normal-weight C144 model to 13.38% (RBMA). The final main consumer of energy for the normal-weight Phoenix models was the fan usage. The fan usage percentage decreased from 12.59% for the C144 model to 12.44% for RBMA.

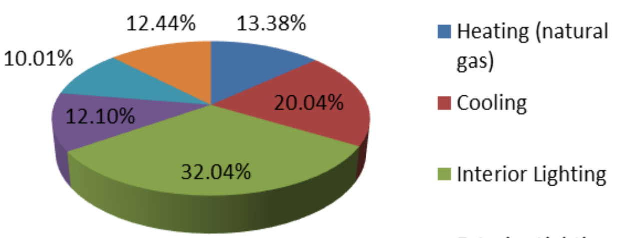

Figure 11. Phoenix, AZ, Strip Mall Normal-Weight Concrete Masonry Model with RBMA Mortar Annual Energy Consumption by End-Use

The lightweight concrete masonry model increased in energy end-use efficiency for heating, cooling, and fan usage. Heating increased by 0.94%, cooling increased by 3.23%, and fan usage increased by 6.14%, for a total increase in energy end-use efficiency of 1.45%. The lightweight RBMA model increased energy consumption efficiency by 1.15%. Any of these options would be an energy efficient replacement in Phoenix for the DOE steel-frame reference model. Unlike the lightweight models, the normal -weight models increased in energy consumption for all models. The normal-weight C144 model decreased by 4.99% and the normal-weight RBMA model decreased by 4.49% in energy efficiency. According to the data the lightweight concrete masonry building envelope responded to high-heat climate conditions better than the normal-weight concrete masonry and steel-frame reference models. Due to the reduction in energy consumption, any of the lightweight concrete masonry options would be ideal.

Hourly heating and cooling energy consumption over peak temperature weeks for winter and summer were analyzed for the EnergyPlus model results. Results of the models were analyzed by separating them into lightweight model results and normal-weight model results, then comparing them to the DOE reference model results for winter and summer. The heating energy consumption difference between the lightweight model and lightweight recycled aggregate mortar models and the DOE reference model was no greater than 1.10 GJ. The lightweight RBMA model operated for a total of 97 hours over eight days. The lightweight C144 model number of heating operating hours deviated only slightly from the other model with 95 hours. The DOE reference model only consumed a total of 12.934 GJ over 75 hours for the entire peak week in January, whereas the lightweight C144 and RBMA models consumed a total of 12.832 GJ and 13943 GJ. Only a slight decrease in energy efficiency occurred. The lightweight C144 model and RBMA model experienced decreases of 6.95% and 7.80% in energy efficiency, respectively. The lightweight C144 model performed the best. The moderate heating energy usage was due to the less extreme winter temperatures experienced in Phoenix. The normal-weight C144 model and normal-weight recycled aggregate mortar models experienced a similar amount of hours for heating operation. Hours of heating operation for the normal-weight models were 94 (C144) and 97 (RBMA).

Even though the normal-weight C144 model operated heat the fewest number of hours for the normal-weight models, it consumed the largest amount of energy at 15.399 GJ. Energy consumption for the remaining model was 15.383 GJ for the normal-weight RBMA model. The normal -weight models deviated from the C144 model about 2.4 GJ. Unlike the lightweight models, the normal-weight models experienced a large decrease in energy efficiency. The normal-weight C144 model decreased 19.06% and the normal-weight RBMA model decreased 18.94%. Of the two normal -weight models, the RBMA model performed the best. Overall, the lightweight concrete masonry models did not stray far from each other for the amount of heating energy consumed. This trend was also true for the normal-weight concrete masonry models. The DOE reference model remained the best option for a more energy efficient building, due to the increased energy consumption for heating during the peak winter temperatures in Phoenix.

From July 1st to July 8th, cooling consumption data were recorded every hour for the lightweight concrete masonry models and the DOE reference model. The cooling system ran for a moderate amount of the day, due to the mixed-humid climate and hot summer weather. The lightweight concrete masonry models consumed more energy over the first week of July than the DOE reference model. Even though the DOE reference model consumed more energy during peak hours, the weekly total energy consumption was 11.004 GJ, which was less than all of the lightweight models. Cooling energy consumption numbers for the lightweight models were 11.024 GJ for the C144 model and

11.152 GJ for the RBMA model. All of the lightweight models required 109 hours to cool the facility, which was four hours more per week than the DOE reference model.

The increase in cooling energy consumption for the lightweight models correlated with the increase in the amount of hours required to cool the facility. There was a slight decrease in energy efficiency for the lightweight models. The C144 model decreased 0.18% and the RBMA model decreased 1.34. Overall, the lightweight C144 model performed the best. Like the lightweight concrete masonry models, the normal-weight models consumed more energy cooling the strip mall in Phoenix than the DOE reference model. The normal-weight models consumed 12.785 GJ over 112 hours for the C144 model and 12.727 GJ over 111 hours for the RBMA model. The DOE reference model only consumed 11.004 GJ over 105 hours. The normal-weight models were considerably less energy efficient than the lightweight models. The normal-weight C144 and RBMA models decreased in energy efficiency by 16.19% and 15.66%, respectively. The lightweight and normal-weight models both consume more energy than the DOE reference model while cooling the strip mall. Of the alternative building envelope constructions, the lightweight models were the closest in cooling energy consumption to the DOE reference model. In conclusion, the DOE reference model outperformed the lightweight and normal-weight models and was also the most energy efficient option.

Conclusions

The U.S. Department of Energy (DOE) reported in 2012 that the building industry was the largest consumer of natural resources and electricity. In order to address the impact of the construction industry on the environment, the use of raw, virgin aggregate and energy efficiency must improve. Commercial building energy consumption is currently being addressed by the building sector by investigating new materials, building envelopes, and energy efficiency best practices. Growth in the new construction sector places a higher demand on natural aggregate, resulting in an escalation in natural aggregate costs. The focus of this current study was to determine the impact on specific heat capacity and thermal conductivity using recycled demolition waste aggregates in masonry mortar and grout applications. A possible solution for reducing demand on natural aggregates is the use of expanded slate and recycled brick aggregate in masonry mortar applications.

In this study, the thermal properties of the recycled aggregate mortar were obtained from previous studies in order to create a comparative analysis between the DOE strip mall steel-frame model, normal-weight and lightweight concrete masonry models, and normal-weight and lightweight recycled aggregate models in the EnergyPlus BESP. The objectives achieved by this study were:

- A model using building energy simulation programs (BESP) for a concrete masonry structure using recycled aggregates was developed and validated by creating a model in EnergyPlus and comparing the results to the DOE results.
- Models for each masonry mortar aggregate were successfully developed and simulated.
- A comparative analysis of annual energy consumption by end-use, the annual building utility performance summary, the heating, cooling, and fan energy usage for peak winter and summer weeks, and the total annual cost and utility usage were performed. Results indicated that the recycled aggregate mortar models performed as well or better than the lightweight and normal-weight masonry systems.

The model results showed that in Miami, FL, the concrete masonry models did not perform as well as the DOE reference model; however, the recycled aggregate mortar models performed as well as and sometimes better than the lightweight and normal-weight concrete masonry models. During the peak summer week, the normal-weight expanded slate and normal-weight C144 models decreased in energy efficiency by 7.60% and 7.80%, respectively. A similar outcome was observed for the peak winter week also. The normal-weight expanded slate and normal-weight C144 models decreased in energy efficiency by 17.45% and 20.82%, respectively. The lightweight C144 model proved to be most energy efficient for both heating and cooling. The lightweight expanded slate model actually increased in energy efficiency by 2.89% while heating.

A percent decrease was experienced in Phoenix, AZ, for both cooling and heating energy efficiency. The most energy efficient models for cooling energy efficiency were the lightweight C144 and normal-weight expanded slate models. These models experienced decreases of 0.18% and 15.36% in energy efficiency, respectively. The heating energy consumption performed similarly except that the decrease in energy efficiency was greater. The lightweight C144 model and the normal-weight expanded slate models performed the best, with decreases of 6.95% and 18.83% energy efficiency, respectively. Although there was a decrease in energy efficiency for all of the models, the recycled aggregate mortar models performed as well as or better than the C144 concrete masonry models. The energy use model results showed that the RBMA models consistently performed as well as, if not better than, the lightweight and normal-weight C144 models. By replacing sand with RBMA in mortar mixes, a more environmentally conscious material can be created. Recycled aggregate mortar will help to reduce demolition waste aggregates, maintain competitive aggregate costs, decrease the need for new quarrying sites, and contribute to a more sustainable building envelope design.

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Biographies

THOMAS NICHOLAS II, PhD, PE, is the Undergraduate Program Coordinator and Assistant Professor of Civil Engineering Technology and Construction Management at UNC Charlotte. Dr. Nicholas holds graduate degrees from West Virginia University (MSCE) and UNC Charlotte (PhD), and is a registered professional engineer in North Carolina. Dr. Nicholas may be reached at tnichola@uncc.edu

TARA L. CAVALLINE, PhD, PE, is an assistant professor of Civil Engineering Technology at UNC Charlotte. She holds BS and MS degrees in Civil Engineering from the Pennsylvania State University and a PhD in Infrastructure and Environmental Systems from UNC Charlotte and is a registered professional engineer in North Carolina. Dr. Cavalline may be reached at Tara.Cavalline@uncc.edu

DIXIE JOHNSON is an undergraduate research assistant in Civil Engineering Technology and Construction Management at UNC Charlotte. Ms. Johnson may be reached at djohn223@uncc.edu

MORGAN LANEY holds BS and MS degrees in Civil Engineering Technology and Construction Management from UNC Charlotte. Mr. Laney may be reached at mlaney@uncc.edu