Re-Pulped Waste Paper-Based Composite Building Materials with Low Thermal Conductivity

Vachira Sangrutsamee\(^1\), Panya Srichandr\(^2\) and Nuchthana Poolthong\(^2\)

\(^1\)Dr. Eng. Candidate, Integrated Product Design and Manufacturing Program, School of Energy, Environment and Materials, King Mongkut's University of Technology Thonburi, Thailand
\(^2\)Assistant Professor, Integrated Product Design and Manufacturing Program, School of Energy, Environment and Materials, King Mongkut's University of Technology Thonburi, Thailand

Abstract

This paper presents an investigation on the properties and applications of paper-based composites. The materials composed of cement, sand and re-pulped waste paper. The physical, mechanical and thermal properties of various types of paper composites were determined. The results showed that the addition of re-pulped waste paper causes high water absorption and leads to a reduction in thermal conductivity, bulk density and compressive strength. Sample mixtures containing re-pulped newspaper, office paper or any type of mixed paper have similar property values. The one exception was samples made from re-pulped carton paper which had a lower thermal conductivity and a lower bulk density than the others. When the proposed blocks were manufactured for comparison with existing masonry blocks, they were shown to satisfy the basic requirements of affordable insulating building materials and to support energy-saving and environmental conservation goals.

Keywords: waste paper recycling; low thermal conductivity; fibre cement; building material; waste paper based composite

1. Introduction

In Thailand, housing construction, particularly for low-income groups, is still confronted with the problem of low quality building materials. Traditional building materials such as clay-brick, soil-cement blocks and concrete blocks are poor insulators based on modern, energy-conscious standards. Consequently, a variety of methods have been developed to enhance the insulation level of these materials.

Large quantities of lignocellulosic waste are being generated worldwide. Agriculture and construction are just two examples of the many sources of waste. This accumulation of waste leads to serious environmental concerns. However, the use of this waste is already reducing the magnitude of the problems of cement-bonded construction materials (Krade, 2010). Previous research has found that the use of waste and natural cellulose fibres as reinforcement in cement composites has enormous potential in the field of recycled materials for building construction. Khedari \textit{et al.} (2001, 2005) reported that using waste agricultural fibres (young coconut and durian peel) in composite building materials results in lower thermal conductivity and bulk density for the final material. Modry (2001) developed a hollow concrete block using recycled paper waste. The results were similar to using expanded slate as an aggregate. The thermal and sound insulation tests conformed to the requirements for partition walls. Decard \textit{et al.} (2001) studied the response of recycled paper waste concrete and concluded that it has a much softer response and a higher damping and energy absorption. Manuel (2002) found that it is an environmentally friendly material due to the significant recyclable content of waste paper content. Therefore, an investigation into the use of waste paper in composites as alternative building materials could solve problems concerning the quality and affordability of building materials and simultaneously ameliorate the associated environmental concerns.

Paper is an example of a valuable material that can be recycled. Disposable paper available in abundance throughout world is composed mainly of short, natural, cellulose fibres and is already used in many local raw materials. Waste paper comes from various sources such as newspaper, office and printing papers and boxes. Each has a different type of fibre quality, and mixing all these papers of different qualities will reduce the purity of the highest quality fibre. The quality of the waste determines the end quality of the
recycled paper. Therefore, an investigation concerning the potential of the different re-pulped waste paper types as construction materials is essential in order to gain an insight into their behaviour and properties.

The objective of this study is to explore the potential use of re-pulped waste paper-based composite as an alternative building material. The influences of waste paper type and content on key properties of the composite will be investigated. Comparisons with existing traditional building materials will also be made.

2. Materials and Experiment Methodology

2.1 Raw materials

The following raw materials were used:

(i) Portland cement: Type I Portland cement, which complies with ASTM C150 - 89 was used.

(ii) Sand: Local natural river sand that passes ASTM sieve number 8 (2.38 mm). The size of sand was about $0.7 \pm 0.145$ mm.

(iii) Mixing water: The main water supply of the province was used.

(iv) Waste paper: Four different types of re-pulped waste paper were collected from disposed office and house papers and were separated into newspaper, office document paper, carton paper and all other mixed papers. The characteristics of recycled pulps are presented in Fig.1.

2.2 Specimen preparation

The mix details of recycled waste paper pulps are presented in Table 1.

The procedure for preparing specimens was conducted as follows:

(i) Weigh waste paper and water according to the desired ratio, as shown in Table 1., and then soak the waste paper in water for 24 h. After that, stir the waste paper using a mechanical stirrer for 10 min. This slurry is called waste paper sludge.

(ii) Weigh sand and cement according to the desired ratio, as shown in Table 2. Mix the sand and cement elements into the paper sludge and then mix well using a mechanical stirrer for 5 min.

(iii) Cast a specimen by pouring the above mixture into a mould and leave it for 3 h. Then remove the mould.

(iv) Cure the specimen at room temperature for 28 days before testing.

2.3 Test methods

The composite specimens were tested based on the following testing standards:

- Physical properties (dimension, shape, bulk density and water absorption): Performed according to ASTM C 134-88. Shaped specimens were dried at laboratory conditions ($24^\circ C$, $56\%$ relative humidity (RH)) and then dried to a constant weight at $105^\circ C$ in the oven.

- Mechanical properties (compressive strength): Measured according to ASTM C 109/C 109-95. Before testing, the 100-mm-side cube specimens must be incubated at room temperature for 28 days.

- Thermal properties (thermal conductivity): Tested according to JIS 2618 at $40^\circ C$ for thermal conductivity with temperature at $24^\circ C$, RH $56\%$.

Three replicate samples were prepared for testing resulting in 48 specimens: four mixing ratios for each of the four mixed pulp types and three replicates of each of these 16 specimens. Five proposed blocks were manufactured and tested as explained in the following testing sections.

Table 1. Mix Details of Composite Specimens

| Types of re-pulped waste paper (Code) | Volume ratio mixture | Pulp content (% by mass of cement) |
|--------------------------------------|----------------------|-----------------------------------|
|                                      | Cement:Sanding:Waste paper pulp |                                  |
| Newspaper (NP)                       | 1:1:0.20             | 20%                               |
|                                      | 1:1:0.40             | 40%                               |
|                                      | 1:1:0.60             | 60%                               |
|                                      | 1:1:0.80             | 80%                               |
| Office paper (OP)                    | 1:1:0.20             | 20%                               |
|                                      | 1:1:0.40             | 40%                               |
|                                      | 1:1:0.60             | 60%                               |
|                                      | 1:1:0.80             | 80%                               |
| Carton paper (CP)                    | 1:1:0.20             | 20%                               |
|                                      | 1:1:0.40             | 40%                               |
|                                      | 1:1:0.60             | 60%                               |
|                                      | 1:1:0.80             | 80%                               |
| Mixed papers (MP)                    | 1:1:0.20             | 20%                               |
|                                      | 1:1:0.40             | 40%                               |
|                                      | 1:1:0.60             | 60%                               |
|                                      | 1:1:0.80             | 80%                               |

Notes: Water content is $0.5 \times$ cement $+ 1.5 \times$ pulp of referenced volume by weight.

The photographs show the re-pulped fibre characteristics of different types of waste paper seen through a scanning electron microscope, X3000.
3. Results and Discussion

To facilitate comparisons, Table 2 grouped the results of the property measurements.

3.1 Compressive strength and bulk density

The variations of the compressive strength with different types and contents of re-pulped waste paper are shown in Fig.2. The effects of the compressive strength decreased with a significant increase in the pulp content. A very high pulp to cement ratio leads to brittleness. This is due to the fact that increasing the content of cellulose fibre pulp (low strength pulp) yields a lot of void in the specimen (Fig.3.). Therefore, this leads to a lower compressive strength and bulk density (Paramisivam et al., 1984 and Swamy, 1988). The relationship between the compressive strength and density is shown in Fig.4.

The SEM observations of the interfacial transition zone contrast the poor bonding of particles with cement paste (Fig.3.). Thus, it results in an increase in tiny voids and porosity in the matrix.

The influence of different re-pulped waste paper types on each mixture ratio is a small variation of the compressive strength and bulk density. This may be because the structural characteristics and physical properties of the pulps show very few differences.

All the specimens with the mixture ratios 60% re-pulped paper or less pass the required standard of non-load bearing masonry units which is greater than 2.54 MPa based on ASTM C 129. Specimens with a re-pulped waste paper content mixture ratio of 80% do not meet the standard.

3.2 Water absorption and bulk density

Fig.5. shows the effects of water absorption and bulk density on the samples of different types and pulp content.

Table 2. Average Measured Properties of the Samples

| Pulp content (%) | Sample Code | Bulk density (Kg/m³) | Water Absorption (%) | Thermal Conductivity (W/m K) | Compressive Strength (MPa) |
|------------------|-------------|----------------------|----------------------|-----------------------------|--------------------------|
| 20%              | NP_20       | 1422.80 ± 3.40       | 20.89 ± 0.33         | 0.6292                      | 6.22 ± 0.03               |
|                  | OP_20       | 1420.40 ± 7.81       | 21.46 ± 0.72         | 0.6250                      | 6.12 ± 0.00               |
|                  | CP_20       | 1418.67 ± 14.85      | 23.48 ± 0.74         | 0.6211                      | ±0.11 ± 6.02              |
|                  | MP_20       | 1420.00 ± 9.24       | 23.08 ± 1.08         | 0.6217                      | 6.17 ± 0.10               |
| 40%              | NP_40       | 1289.67 ± 20.37      | 25.61 ± 0.37         | 0.5125                      | 4.85 ± 0.15               |
|                  | OP_40       | 1288.00 ± 4.62       | 25.11 ± 0.98         | 0.5106                      | 4.74 ± 0.07               |
|                  | CP_40       | 1270.67 ± 14.85      | 28.01 ± 0.67         | 0.5106                      | ±0.17 ± 4.68              |
|                  | MP_40       | 1276.00 ± 18.90      | 27.02 ± 0.92         | 0.5173                      | 4.69 ± 0.12               |
| 60%              | NP_60       | 1229.65 ± 17.88      | 31.77 ± 0.34         | 0.4561                      | 3.18 ± 0.05               |
|                  | OP_60       | 1122.67 ± 11.85      | 31.99 ± 0.50         | 0.4536                      | 3.16 ± 0.03               |
|                  | CP_60       | 1096.00 ± 10.07      | 34.58 ± 0.30         | 0.4454                      | ±0.07 ± 3.07              |
|                  | MP_60       | 1104.00 ± 12.86      | 33.50 ± 1.31         | 0.4563                      | 3.09 ± 0.03               |
| 80%              | NP_80       | 972.12 ± 22.09       | 57.41 ± 1.19         | 0.2903                      | 1.42 ± 0.06               |
|                  | OP_80       | 968.00 ± 12.22       | 57.60 ± 0.27         | 0.2890                      | 1.33 ± 0.03               |
|                  | CP_80       | 960.00 ± 14.42       | 59.23 ± 0.53         | 0.2863                      | ±0.10 ± 1.24              |
|                  | MP_80       | 961.33 ± 7.06        | 58.31 ± 0.92         | 0.2870                      | 1.29 ± 0.01               |

Fig.2. Compressive Strength of Composites Versus the Waste Paper Pulp Content for Different Types of Recycled Waste Paper

Fig.3. SEM Micrograph of the Specimen with Re-Pulped Newspaper (2000X)

Fig.4. Compressive Strength and Bulk Density of the Composites

The pulp properties of the pulps show very few differences.

All the specimens with the mixture ratios 60% re-pulped paper or less pass the required standard of non-load bearing masonry units which is greater than 2.54 MPa based on ASTM C 129. Specimens with a re-pulped waste paper content mixture ratio of 80% do not meet the standard.

3.2 Water absorption and bulk density

Fig.5. shows the effects of water absorption and bulk density on the samples of different types and pulp.
contents. The results indicate that the presence of a high amount of recycled waste paper in the mixture yields high water absorption. Although there are small variations in the specimen properties for different recycled waste papers, all the re-pulped carton paper-based composite specimens seem to have higher water absorption and lower bulk density than the others. The relationship between the water absorption and bulk density is shown in Fig.6. The water absorption decreases when the density increases. As a result, the spaces in the low-density samples are larger than those in the high-density samples of the same thickness. Consequently, larger spaces in the low-density specimens occurred, through which water was able to penetrate into the specimens more easily than into the high-density samples. In fact, water absorption is inversely proportional to the fibre cement board density (Asasutjarit et al., 2007).

3.3 Thermal conductivity and bulk density
The effect of re-pulped waste paper content on thermal conductivity is shown in Fig.7. As expected, when the quantity of the pulp content increased, the thermal conductivity and bulk density decreased. The relationship between the thermal conductivity and bulk density is shown in Fig.8. It is well demonstrated that the manufactured samples have a relatively low thermal conductivity, varying between 0.2890 and 0.6250 W/m K. Obviously, low-density samples have low thermal conductivity because the extent of spaces and voids in the samples increase considerably. The thermal conductivity of a porous medium is inversely proportional to the extent of voids in the specimen. So, it can be concluded that the heat-insulating efficiency of a material is inversely proportional to its density (Salas et al., 1986).

The re-pulped carton paper in all the mixtures seems to have lower thermal conductivity than the others. This may be because the characteristics of carton pulp include shorter pulp and higher parenchyma content than the re-pulped waste paper. In general, it is more difficult to align and pack shorter fibres more densely than the longer ones (Morrissey et al., 1985). Therefore, it has more voids resulting in a lower thermal conductivity.

3.4 Comparison of the proposed blocks with local commercial blocks
Five experimental blocks with a weight ratio of 1:1:0.60 (cement: sand: re-pulped waste paper) (60% of all the mixed re-pulped waste paper) were prepared and tested with the nominal block size as a standard: 7.5 cm × 40 cm × 20 cm. The experimental blocks, existing concrete blocks and clay bricks are shown in Fig.9. The test results are summarized in Table 3. We can conclude from the results that;
- Thermal conductivity is lower than that of the...
existing masonry blocks. Therefore, it could be used to prevent heat transfer into buildings, and thus save energy.

- Compressive strengths are less than that of the clay bricks, but are higher than that of hollow core concrete blocks and are still in the standard range for hollow non-load bearing concrete masonry units (ASTM C129). Therefore, it is possible to construct housing walls with them.

- Water absorption of the experimental blocks is higher than that of the existing masonry blocks. Its outside surface should be coated and plastered for protection against rain and humidity if applied to outside walls.

- Appearance densities are higher than those of the existing masonry blocks. But interestingly, the solid bulk densities are lower.

Table 3. Comparison between Experimental Blocks and Existing Commercial Blocks

| Properties            | Clay bricks | Hollow core concrete blocks | Experimental blocks |
|-----------------------|-------------|----------------------------|---------------------|
| Thermal conductivity  | 1.15        | 0.519                      | 0.4538              |
| (W/m K)               |             |                            |                     |
| Compressive strength  | 3.5         | 2.8                        | 3.23                |
| (MPa)                 |             |                            |                     |
| Water absorption (%)  | 22          | 20                         | 31.61               |
| Appearance density    | 1569        | 972                        | 1163.8              |
| (kg/m³)               |             |                            |                     |

Fig.9. Photographs of (a) Clay Bricks, (b) Hollow Core Concrete Blocks and (c) Experimental Blocks

4. Conclusion

The experimental investigation of the potential of the utilization of recycled waste paper to manufacture the components of local and low cost construction materials showed that it is an extremely attractive option. The following conclusions were obtained:

- Addition of re-pulped waste paper leads to reduced thermal conductivity and bulk density of cement composites.

- The small variations in the properties of cement composites depend on the structural and physical characteristics of the re-pulped waste paper types. Re-pulped carton paper is the most effective lightweight raw material that reduces the thermal conductivity and density of cement composites, but such re-pulped paper results in lower compressive strength and higher water absorption of the composite.

- The proposed block has a weight ratio of 1:1:0.6 (cement: sand: re-pulped waste paper). Its compressive strength passes the required standard of non-load bearing masonry walls (ASTM C129). Its properties are as follows: a thermal conductivity of 0.4538 W/m K, a compressive strength of about 3.23 MPa, a bulk density of 1163.8 kg/m³ and water absorption of 31.61%.

- Comparison of the physical, mechanical and thermal properties of the experimental blocks to local commercial blocks demonstrated their excellent characteristics. They have the additional property of being light in weight with low thermal conductivity.

Finally, using recycled waste paper as a local affordable construction material could be a key factor in the development of sustainable and low thermal conductivity building materials for local people around the country while at the same time helping in saving energy and the conservation of the environment.

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