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PROPORTION AND PROPERTY SPECIFICATIONS AND STRENGTH BEHAVIOR OF MORTAR USING WOOD ASH AS PARTIAL REPLACEMENT OF LIME

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ABSTRACT: Wood ash is produced by the incineration of wood and wood products; thus, it is a waste product generated from various sources such as household fireplaces, agricultural activities, or manufacturing plants. By reusing wood ash wastes as lime-replacement additives, the resulting lime mortar would become a more practical building material. This study utilized varying proportions of wood ash (25%, 50%, 75%, and 100%) as partial replacement of lime in manufacturing Type N mortars through the provision of proportion and property specifications that adhere to known industry standards. The proportion specification for Type N Mortar was modified as one-part Type 1 Portland cement, one-part Type S Hydraulic Lime and/or wood ash, and six parts of coarse sand aggregate (1:1:6). The air content, initial and final setting times, 7- and 28-day compressive strengths of the mixed mortars had been considerably affected by the presence of wood ash within the mortar mix. Furthermore, the use of wood ash as a partial replacement of lime caused an increase in air content and a decrease in setting times of the mortar mix. Mortars with 100% replacement of lime with wood ash showed the highest compressive strength for both 7- and 28-day tests. Therefore, the incorporation of wood ash as a lime replacement was determined to be a viable option for Type N mortars.

Keywords: Air content, Compressive strength, Mortar, Setting time, Wood ash

1. INTRODUCTION

In construction, mortars are building materials that fill the gaps between blocks of a structure; these materials typically comprise fine aggregates, a binder, and water. According to [1], the different types of mortars are categorized by its binding material: earth mortar, cement-sand mortar, gypsum mortar, and lime mortar. Lime mortar is comparable to other mortar types except for its breathability; this provides flexibility and strength to the structure. In terms of plasticity and workability, a lime mortar can quickly adhere to blocks as it can accommodate changes in moisture within the masonry construction. It also reduces the potential damage caused by the accumulation of salt from the weathering of the blocks [2].

Lime mortar serves as sacrificial layers that preserve structures from excessive exposure against mechanical and environmental influences. These mortars are both cohesive and adhesive to the structure. It is necessary to choose the right materials, formulation, and preserving conditions of the mortar to meet functional and aesthetic requirements and fulfill the principles of compatibility, while maintaining the structure's integrity and durability [3]. Lime is a weaker element than stone, brick, or cob, which enables it to resist cracking from a certain amount of movement. When the lime mortar is applied, it is much easier and simpler to repair [4].

The trend of using lime mortar certainly altered due to the difficulties experienced during the application of lime mortars; these problems include weak mechanical properties, long setting times, and hardening times, especially at a very high relative humidity [5]. Lime mortar is not water-resistant, but it allows the wall block to breathe. However, segregation of the original material and the lime might occur as the mortar dries and hardens. The resulting mortar will be weakened because of a poorly-formed pore structure; thus, it will be susceptible to frost damage and deterioration.

This study aimed to fill the gap of previous studies, wherein most literature focused on testing the strength behavior of the mortars using various lime-replacement additives such as slags and ashes. Several studies about wood ash [6-7] discovered the potential use of wood ash in several applications such as mortar and concrete production, and forest road construction; however, most studies lacked focus on the importance of the proportion and property specifications of wood ash in manufacturing lime mortars.

This study generally aimed to utilize wood ash as a partial replacement of lime in manufacturing mortars for masonry construction. Specifically, this study addressed the following objectives: (1) to determine the proportion specification of the mortars with 0%, 25%, 50%, 75%, and 100% replacement of lime by wood ash conforming to the requirements of American Society for Testing and Materials (ASTM) C270, and (2) to compare the property specifications of the mixed mortars in terms of setting time, air content, and compressive strength.

This study had contributed to the development of the masonry construction industry. Wood ash is a waste product generated by the incineration of wood and wood products; various sources of wood ash include but are not limited to household fireplaces, agricultural activities, or manufacturing plants. By reusing wood ash wastes as lime-replacement additives, the resulting mortar would become a more practical building material. Also, the process of lime production involves the emission of large quantities of carbon dioxide, which contributes to global climate change [8]. The partial replacement of lime with wood ash wastes could lessen environmental problems associated with manufacturing mortars, such as air, water, and soil pollution. Thus, this study can significantly contribute to achieving sustainable development by reducing the ecological footprint of disposing wood ash and manufacturing lime mortars.

This study is limited only to the concept of specifying the proportion, properties, and compressive strength of the mortars mixed with wood ash as partial replacement of lime. However, this study does not indicate the specific type of wood burnt to generate wood ashes. The researchers used the American Society for Testing and Materials (ASTM) C270 [9] as the standard specification for mortars used in unit masonry. In conformity with the American Association of State Highway and Transportation Officials (AASHTO) standard specifications, different mortar testing equipment were used such as a flow table to measure air content (AASHTO T 137-04) [10]; a Gillmore needle to measure setting time (AASHTO T 154-06) [11]; and a Universal Testing Machine (UTM) to measure the compressive strength of the mortars (AASHTO T 106M/T 106-07) [12]. However, as a consequence of time constraints, the preliminary tests for the compressive strength of the mortars were conducted only after 7 and 28 days of curing.

2. METHODOLOGY

In conformity to both American Society for Testing and Materials (ASTM) and American Association of State Highway and Transportation Officials (AASHTO) standard specifications, this section presents the different procedures and equipment used in the study.

2.1 Material Sourcing and Preparation

The mortars had comprised of the following components: lime, cement binder, aggregate, and water. Type S Hydrated Lime conforming to ASTM C-207 was used in the study. Type 1 Portland cement was also used as the binder as specified in ASTM C-150. A well-graded coarse sand aggregate (4.75 mm in diameter) was used. Wood ashes were utilized as partial lime-replacement additives; the ashes were collected from household fireplaces. Water was prepared and kept free from oils, acids, alkalis, salts, organic materials, or other substances that were deleterious to mortar.

2.2 Preparation of Lime Mortar with Varying Proportions of Wood Ash as Lime Replacement

In accordance with ASTM C270 [9], several batches of Type N Mortar were made with a mortar mix ratio of one-part Portland cement, one-part hydrated lime, and six-parts sand (1:1:6). However, the hydrated lime was partially replaced with varying proportions (25%, 50%, 75%, and 100%) of wood ash. Proportion specifications of the mortars were determined depending on the sample weight required by each test. A reference mortar containing 0% wood ash and 100% lime was also evaluated.

2.3 Determination of Air Content (AASHTO T 137-04)

Mortars were mixed using 350 g of cement to 1400 g of 20-30 standard sand and sufficient water to give a flow of 87.5 ± 7.5%. A layer of mortar about 25 mm in thickness was placed in the mold and tamped 20 times to ensure uniform filling of the mold. An approximately 20-mm layer of mortar was added to the top of the mold and tamped again. The mortar was separated from the mold and then placed on a planar surface. Prior to determining the air content of the mortar, its flow rate was calculated using Equation (1):

$$R_{flow} = \frac{D_{mold}}{D_{mortar}} \times 100\% \tag{1}$$

where R_{flow} is the flow rate (in percent), D_{mold} is the diameter of mold (in mm), and D_{mortar} is the diameter of mortar (in mm). The flow table and mold used were conforming to the requirements of AASHTO 152M/M 152 [10]. The flow table should be clean and dry, so any water from around the edge of the mold was removed. After mixing the mold, the tamping rod of the flow table should be dropped onto the mortar 10 times. The average diameter of the mortar mass increases with each drop, and this corresponding increase in diameter is known as the flow rate. Several trial mortars with varying percentages of water were made until the desired flow of 87.5 ± 7.5% was obtained.

Air content of the mortar was determined using the mass of 400 mL of mortar and the physical properties of its components used, as shown in Eq. (2) and Eq. (3):

$$D = \frac{W_1 + W_2 + V_w}{\frac{W_1}{S_1} + \frac{W_2}{S_2} + V_w} \quad (2)$$

$$A = 100 - \frac{W_m}{4D} \quad (3)$$

where D is the density of air-free mortar (in g/cm^3), W_1 is the mass of cement (in grams), W_2 is the mass of sand (in grams), W_m is the mass of 400 mL of mortar (in grams), V_W is the millilitres-gram of water used (in mL-g), S_1 is the density of cement (in g/cm^3), S_2 is the density of standard sand (2.65 g/cm^3), and A is the volume percent of entrained air (%). The ratio of mixing water and binding materials of the mortars was compared with the resulting air content. The ratio of mixing water to the binding materials corresponds to the volume of mixing water (in mL) divided by the total mass of binding materials (cement ± lime ± wood ash) used (in grams).

2.4 Determination of Setting Time (AASHTO T 154-06)

Mortars were produced in batches using 650 g of cement with the percentage of mixing water required for normal consistency. To mold the mortars, a pat was made with a flat top by drawing the trowel from the outer edge toward the center. The prepared mortars were tested to meet the required consistency using the needles of the Gillmore apparatus. The time required to obtain the stipulated penetration of the Gillmore needle is the time of setting. The needles were held in a vertical position and applied lightly to the surface of the pat. The initial set was acquired when the initial Gillmore needle touched the surface of the pat without appreciable indentation. The Gillmore initial time of setting was determined when the elapsed time, in minutes, between the time of contact of mortar and the time when the mortar acquired its initial set. The final set was also acquired when the final Gillmore needle touched the surface of the pat without appreciable indentation. The Gillmore final time of setting was determined when the elapsed time, in minutes, between the time of contact of mortar and the time when the mortar acquired its final set.

2.5 Compressive Strength Testing (AASHTO T 106M/T 106-07)

Compressive strength tests were conducted on the mortars that were proportioned, mixed and conditioned in the testing laboratory. Two-inch mortar cubes were used as compressive strength specimens cast in non-absorbent molds and cured in a moist room and conditioned in the laboratory meeting the requirements of ASTM C511. One-third of the mold was filled with mortar and pressed 25 times with the help of a tampering rod; this procedure of filling and tapping was repeated thrice. A trowel was used to smoothen the upper surface and was kept open air for one day. Afterwards, the cube specimens were cured in a lime bath for 7 and 28 days. To determine the compressive strength of the mortar, the Universal Testing Machine (UTM) was used by applying incremental load to the cube specimen. As the load was applied on the cube, it developed cracks at a certain load. The application of load was stopped when the cube has been crushed. The compressive strength of the mortar was calculated using Eq. (4):

$$f_m = \frac{P}{A} \quad (4)$$

where f_m is the compressive strength of the mortar (in MPa), P is the total maximum load (in N), and A is the area of loaded surface (in mm^2). The compressive strength was reported as an average of two trials.

3. RESULTS AND DISCUSSION

Five (5) sets of mortars with Type 1 Portland cement, well-graded coarse sand, and gradual replacement of Type S Hydraulic Lime with wood ash were tested to determine the appropriate proportion specification with the right volume of mixing water as well as its mechanical properties such as setting time, air content, and compressive strength.

3.1 Proportion Specifications of Lime Mortar with Varying Proportions of Wood Ash as Lime Replacement

Modified from ASTM C270 [9], several batches of Type N Mortar were made with a mortar mix ratio of one-part Type 1 Portland cement, one-part Type S Hydrated Lime and/or wood ash, and six-parts coarse sand aggregate (1:1:6). As presented in Table 1, a total sample weight of 800 grams was used in every batch of mortars in the determination of air content and compressive strength conforming to AASHTO T 137-04 [10] and AASHTO T

106M/T 106-0 [12], respectively. Furthermore, a total sample weight of 650 grams was sampled in every batch of mortars for the determination of initial and final setting times in accordance with AASHTO T 154-06 [11], as shown in Table 2. Upon determination of the proportion specifications, Mortar A is the reference mortar having no partial replacement of lime with wood ash.

Table 1 Mortar Mix Proportions for the Determination of Air Content and Compressive Strength Test (AASHTO T 137-04; AASHTO T 106M/T 106-07)

Sample: 800 g	Cement : Lime : Sand = 1:1:6			
	Cement (g)	Lime (g)	Wood Ash (g)	Sand (g)
Mortar A	100	100	0	600
Mortar B	100	75	25	600
Mortar C	100	50	50	600
Mortar D	100	25	75	600
Mortar E	100	0	100	600

Table 2 Mortar Mix Proportions for the Determination of Initial and Final Setting Times (AASHTO T 154-06)

Sample: 650 g	Cement : Lime : Sand = 1:1:6			
	Cement (g)	Lime (g)	Wood Ash (g)	Sand (g)
Mortar A	81.25	81.25	0	487.5
Mortar B	81.25	60.94	20.31	487.5
Mortar C	81.25	40.625	40.625	487.5
Mortar D	81.25	20.31	60.94	487.5
Mortar E	81.25	0	81.25	487.5

3.2 Air Content

The flow was first determined to identify the ratio of mixing water to the binding materials with the resulting flow of 87.5 +/- 7.5%, as stated in AASHTO T 137-04 [10]. In particular, the mixed mortars got the desired flow between 0.65 to 0.80 ratio of mixing water to the binding materials when the volume of mixing water was varied from 130 – 170 mL. The ASTM C91/ C91M-18 property specification provided an allowable range of 8 - 21% for the air content of Type N mortars [13]. All of the set of mortars have an average air content within the standard range; however, Mortar E with 0% lime and 100% wood ash had the highest air content of 14.58%, as shown in Table 3 and graphically presented in Figure 1. Furthermore, the air content of Mortar E will be at its maximum at 0.65 ratio of mixing water to the binding materials. The air content of mixed mortars generally increased as the amount of wood ash increased. A possible explanation was that the angularity of the wood ash particles as described by [6], allocated larger pore spaces between sand aggregates and binding materials.

Table 3 Experimental Results of Air Content

MW/ BM	Air Content of Mortars (%)				
	A	B	C	D	E
0.65	15.89	17.28	18.54	19.46	20.11
0.70	13.15	15.76	16.12	15.46	16.62
0.75	10.98	14.00	13.86	12.60	14.04
0.80	9.52	12.51	11.06	10.85	12.17
0.85	8.16	9.58	8.98	9.15	9.95

Note: MW/BM means ratio of mixing water to binding materials (cement ± lime ± wood ash).

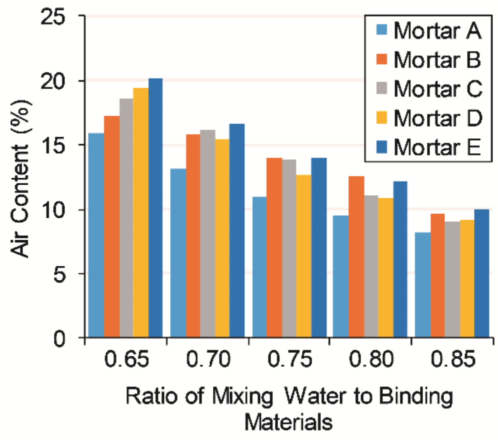

Fig. 1 Relationship between air content and water-to-binding material ratio of the mixed mortars. L means lime and WA means wood ash.

3.3 Setting Time

The AASHTO T-154 [11] limits the initial time of setting on samples testing between 100 to 341 minutes. Basically, the mortar with time closest to 100 minutes is said to have the best initial setting time. As shown in Table 4 and Fig. 2, Mortar C with 50% lime and 50% wood ash has an average initial setting time closest to 100 minutes, having 108 minutes. On the other hand, Mortar A with 100% lime has the longest average of initial setting time. This is similar to the study of [5] which stated that lime mortar shows difficulties including slow setting and hardening times. Moreover, the AASHTO T-154 [11] also limits the final time of setting on samples testing between 239 and 561 minutes. Basically, the mortar with time closest to 239 minutes is said to have the best final setting time. Mortar B with 75% lime and 25% wood ash has an average final setting time closest to a minimum of 239 minutes, having 243 minutes, followed by mortar C which had the best initial setting time. On the other hand, Mortar A with 100% lime has the longest average of final setting time. The initial and final setting times of mixed mortars were drastically reduced when gradual replacement of lime by wood ash (25%, 50%, 75%, and 100%) was involved.

Table 4 Experimental Results of Setting Time

Composition	Setting Time (mins)	
	Initial	Final
Mortar A (100% L; 0% WA)	162	348
Mortar B (75% L; 25% WA)	114	243
Mortar C (50% L; 50% WA)	108	246
Mortar D (25% L; 75% WA)	123	270
Mortar E (0% L; 100% WA)	147	321

Note: L means lime and WA means wood ash.

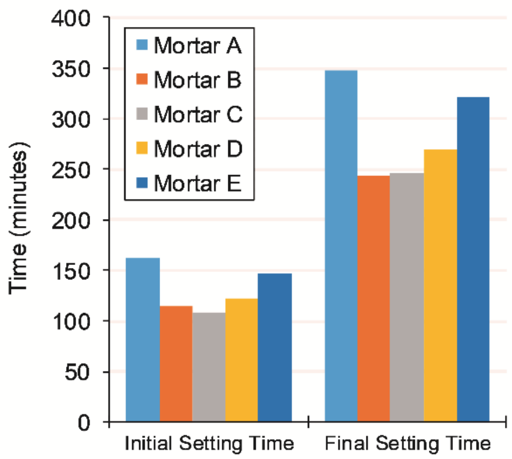

Fig. 2 Relationship between the Initial and Final Setting Times and Wood Ash/Lime Ratio. L means lime and WA means wood ash.

3.4 Compressive Strength

In accordance with ASTM C91/ C91M-18 [13], the compressive strength of Type N mortars should be equal or greater than 3.4 MPa for 7-day test and 6.2 MPa for the 28-day test. As presented in Table 5 and Fig. 3, all of the mortars exhibited 7- and 28-day compressive strengths greater than the specified standards; however, Mortar A has a below standard 28-day compressive strength. Mortar E with 100% wood ash and 0% lime yielded the highest compressive strength for both day-tests. The 28-day compressive strength of mixed mortars was significantly enhanced when varying amounts of wood ash were incorporated. The improved 28-day compressive strengths could be attributed to wood ash as a pozzolanic material, similar to the findings of [14]. Mixed mortars with at least 25% partial replacement of lime with wood ash could possibly be sufficient in exhibiting pozzolanic reaction; however, it is notable that the amount of Type 1 Portland cement was kept constant across all mixed mortars.

Table 5 Experimental Results of Compressive Strength Test

Composition	Compressive Strength (MPa)	
	7-day	28-day
Mortar A (100% L; 0% WA)	4.625	5.185
Mortar B (75% L; 25% WA)	4.590	7.095
Mortar C (50% L; 50% WA)	4.500	6.910
Mortar D (25% L; 75% WA)	4.010	6.540
Mortar E (0% L; 100% WA)	4.935	6.980

Note: L means lime and WA means wood ash.

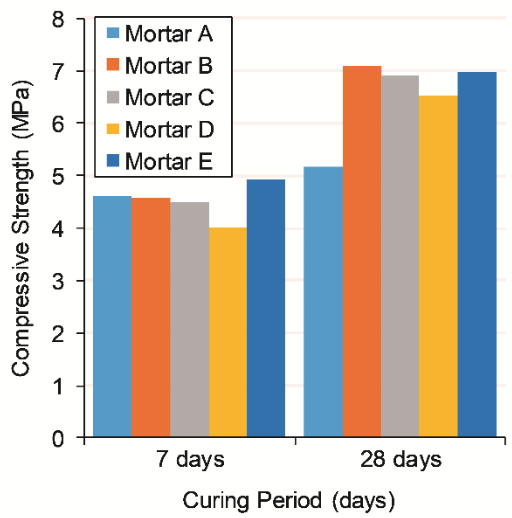

Fig. 3 Variation of Compressive Strength at 7 and 28 days curing period. L means lime and WA means wood ash.

4. CONCLUSIONS

This study aimed to utilize wood ash as a partial replacement of Type S Hydraulic Lime in manufacturing Type N mortars through the provision of proportion and property specifications that adhere to known industry standards such as American Society for Testing and Materials (ASTM) and American Association of State

Highway and Transportation Officials (AASHTO). The air content, initial and final setting times, 7- and 28-day compressive strengths of the mixed mortars had been considerably affected by the presence of wood ash within the mortar mix. Therefore, the following conclusions were made based on the results of this study:

1. Modified from ASTM C270, the proportion specification for Type N Mortar is one part Type 1 Portland cement, one part Type S Hydraulic Lime and/or wood ash, and six parts of coarse sand aggregate (1:1:6). Furthermore, the ideal water-to-binding material ratio was 0.65, wherein the mixed mortars typically exhibited higher air content.
2. Based on the proportion specification of the mortars with 0%, 25%, 50%, 75%, and 100% replacement of lime by wood ash, the following property specifications were most favorable:
   a. The value of air content was highest when lime was completely replaced by 100% wood ash. As the amount of wood ash content increased, the air content significantly increased resulting from the angularity of wood ash particles.
   b. The initial time of setting was fastest when lime was partially replaced by 50% wood ash, whereas the longest initial setting time was observed in the reference mortar. Gradual replacement of wood ash caused the mixed mortars to have significantly faster initial setting times as compared to the reference mortar.
   c. The final time of setting was fastest when lime was replaced by 25% of wood ash. Gradual replacement of wood ash caused the mixed mortars to exhibit significantly faster final setting times as compared to the reference mortar.
   d. Mortars with 100% replacement of lime with wood ash showed the highest compressive strength for both 7- and 28-day tests. Thus, the incorporation of wood ash as a lime replacement is a viable option for Type N mortars.

5. ACKNOWLEDGMENTS

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