Leadership in Sustainable Infrastructure
Leadership en Infrastructures Durables

Vancouver, Canada
May 31 – June 3, 2017/ *Mai 31 – Juin 3, 2017*

USING WASTE WOOD ASH AS CEMENT REPLACEMENT: OPTIMUM TEMPERATURE AND PERCENT REPLACEMENT

Fraser, Tanya[1,2], Bhabra, Ameeta[1] and Rteil, Ahmad[1]
[1] University of British Columbia, Kelowna, BC, Canada
[2] tanya.fraser@alumni.ubc.ca

Abstract: Concrete is one of the leading materials used for infrastructural services worldwide. With new construction and aging pre-existing elements, the use of concrete is expected to increase with the demand of the world's growing population. Portland cement, a major constituent of concrete, accounts for about 5% of the total CO_2 emissions worldwide. For this reason, researchers are trying to find new raw materials that would result in concrete with lower carbon footprint. Wood ash is an abundant waste material produced from the combustion of wood. Roughly 6-10% of the original mass is left as residual ash, of which 70% is disposed in a landfill. Wood ash contains a significant amount of lime (CaO), and depending on its combustion temperature, it may contain cementitious properties. In this study, the use of waste wood ash (WWA) as a partial cement replacement will be investigated. Standard cement mortar cubes were cast with a binder:sand:water ratio of 1:2.75:0.486 and cement replacements of WWA at 10, 20 and 30 percent. The cubes were tested for compressive strength at curing periods of 3, 7, and 29 days. The combustion temperature was also varied, with samples held at 700, 850 and 1000 degrees Celsius for 4 hours in the kiln. Results showed that wood ash treated at 850ºC could replace cement up to 20% by weight.

1 INTRODUCTION

Civil engineering materials are used worldwide for infrastructural services, creating a vast market for an advancement in research. Concrete is one of the most commonly used construction materials on earth, with applications from large scale high-rises and public buildings, bridges, roadways, to pavements, and parking lots. Concrete is a versatile material made up of 4 main components; cement, water, fine and coarse aggregates. Portland cement, being one of the main constituents, is also a large contributor to CO_2 emissions, the primary greenhouse gas that drives climate change. During the production of cement, CO_2 is generated mainly from the fuel used to heat the kiln to the necessary temperature of 1600ºC and the breakdown of $CaCO_3$. It is estimated that for every tonne of cement produced, an equal tonne of CO_2 is emitted into the atmosphere, accounting for about 5% of the total man-made CO_2 emissions worldwide (Humphreys & Mahasenen, 2002). An increase in CO_2 emissions are to be expected with an increase in concrete demand. Researchers are trying to find new raw materials and processes that would result in greener concrete.

One of these materials that have potential to be a cement replacement is wood ash. Wood ash can be primarily found at timber manufacturing plants or thermal power plants. The material is produced through a variety of ways, including burning scrap pieces of wood for easy disposal, heating small scale boilers for industrial processes and combustion for energy production (Cheah & Ramli, 2011). This process typically results in 6-10% of the mass in ash, roughly 70% of which is disposed in a landfill (Siddique, 2012). For adequate cement replacement, the properties of the materials must be comparable to that of cement. Lime (CaO) is one of most significant compounds in wood ash, making it a promising substitute. The amount of CaO can vary greatly from different species of wood ranging from 4-70% (Barathan & Gobinath, 2013). Other major oxides include calcite $CaCO_3$, portlandite ($Ca(OH)_2$) and calcium silicate (Ca_2SiO_4) (Siddique, 2012). The bulk density has been found to be around 490 kg/m^3 and a specific gravity of 2.48 (Cheah & Ramli, 2011). The wood ash grains are typically angular with an average particle size of 230µm and a pH varying between 9 and 13.5 (Siddique, 2012).

In order to activate the cementitious properties shown by waste wood ash (WWA), it is necessary to burn the wood ash at higher temperature than that of the combustion temperate, leading to a decrease in final mass. Studies have shown that with an increase of temperature from 538ºC to 1093ºC, the mass of the wood ash reduced by up to 45%. This partial loss in mass has been found to be due to the evaporation of water that is absorbed in the wood ash as well as the decomposition of calcium and potassium carbonates (Misra, Ragland, & Baker, 1993). The result of burning the large amount of WWA required for adequate cement replacement reduces the use of landfill space and aids in the reduction of CO_2 emissions.

Barathan and Gobinath (2013) completed a study on wood ash as a partial cement replacement by weights in tests of 10%, 20% and 30% after burning wood ash at 600º for 4 hours and passing the ash through a 75µm sieve. The compression tests showed compared to the control of minor losses in strength and even an increase in strength with the 20% replacement at 28 days. It was concluded that the 20% samples showed higher degrees of hydration and compressive strength, which made it the optimal replacement percentage. Another study by Ramos et. al. (2013) found that the WWA tested was in accordance with the European requirements for fly ash (NP EN 450-1) and pozzolans (NP 4420). Compressive strengths were tested at 10% and 20% replacement with WWA as well as durability tests (carbonation and ASR). In terms of strength, both the 10% and 20% replacement maintained the compressive strength of the control mortar. As expected, the carbonation depth achieved in replaced mortar mixes was higher than that of cement mortar. The ASR expansion was reduced compared to neat Portland cement mortar, by 18% and 60% for 10% and 20% replacement respectively (Ramos, Matos, & Sousa-Coutinho, 2013). On the other hand, a study by Elinwa and Mahmood (2002) showed that with a cement replacement of 5% to 30% with WWA, the 28 day strength decreased up to 32%.

2 EXPERIMENTAL STUDY

In this study, mortar cubes with waste wood ash (WWA) treated at 700ºC, 850ºC and 1000ºC was tested for compressive strength at three levels of cement replacement (10%, 20% and 30%) as shown in Table 1. The naming convention used was Wx-Ty, where x and y represent the replacement percentage and the treated temperature respectively. For the control specimens, W0-T0 (1) was compared with the 700ºC and 1000ºC treated specimens whereas the 850ºC specimens were compared with the W0-T0 (2). As the mixes were prepared at separate times during the length of this project, it was essential to compare the specimens treated at 850 ºC with the corresponding control poured at that time.

Table 1: Compressive strength for concrete cubes

Mix name	Wood ash replacement (%)	Treated temperature (°C)
W0-T0 (1)	0	N/A
W0-T0 (2)	0	N/A
W10-T700	10	700
W20-T700	20	700
W30-T700	30	700
W10-T850	10	850
W20-T850	20	850
W30-T850	30	850
W10-T1000	10	1000
W20-T1000	20	1000
W30-T1000	30	1000

For this experiment cement type GU was used. The wood ash was collected from a timber production plant in BC Interior and was conducted over two periods. The first batches were heat treated in a kiln at 700ºC and 1000ºC to remove the remaining organic content. The second batch involved heat treatment in between these two temperatures at 850 ºC. The kiln was held at the proper temperature for 4 hours. Through the burning process a mass reduction average of 70% for all three temperature samples were measured. This initial loss is due to the moisture content of the ash as well as burning the existing carbon. All of the ash that was burned in the kiln was sieved through an 80µm sieve to ensure the similarity in particle size between the WWA and Portland cement being replaced. The use of scanning electron microscope (SEM) helped to characterize the chemical elements that were present in the wood ash for the three testing temperatures. The mix design was composed of the wood ash, ordinary Portland cement, sand and water according to CSA A3000 standard (2013). The ratio of "binder:sand:water" utilized for this test procedure was 1:2.75:0.486. Metallic cube molds of 50mm x 50mm x 50mm in size were used to cast the total eleven mixes (Table 1). Each cube was mixed and compacted following the CSA standard. After curing the cubes in moulds for a 24-hr period they were removed and placed in a curing room. The cubes were cured until they were tested at 3, 7 and 29 days for their compressive strength. A total of three cubes were tested at each testing day for each mix for a total of 99 cubes.

3 RESULTS AND DISCUSSION

The following section will cover the analysis of chemical distribution using a scanning electron microscope (SEM) within the three temperature samples. Additionally, the compressive strength averages of the three temperature groups are compared with that of their respective control groups.

3.1 Chemical Composition

The sieved wood ash samples were analysed using a SEM. For each temperature, the chemical elements were determined from three samples with 20 spectrums from each sample. The elements of one selected spectrum for wood ash burned at 700, 850 and 1000 degrees Celsius can be seen in Figure 1 to 3 respectively. The differences in picture layout are due to the first batch made with 700 ºC, 1000 ºC and the second batch at 850 ºC, with different SEM analysis dates. The average spectrum composition with the element maximum and minimum is shown in Table 2 to 4 for 700ºC, 850ºC and 1000ºC respectively. Photos of the wood ash were taken at magnification levels of 1000x and 5000x for the three temperatures which are displayed in Figure 4. Due to limited resources available for this study, no further chemical composition was explored to determine the compound variation when treating the samples at different temperatures.

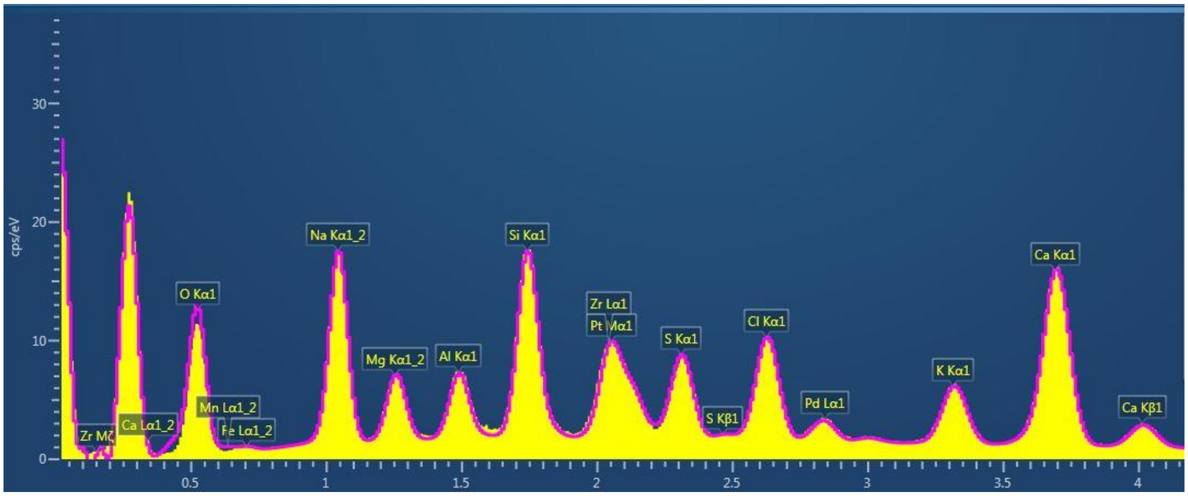
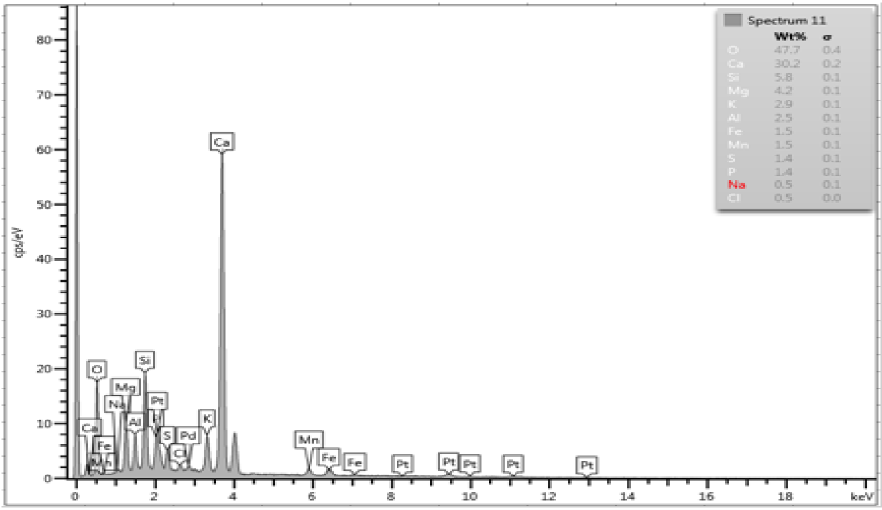


Figure 1: Chemical elements for one sample of wood ash burned at 700 degrees Celsius



Spectrum 11

	Wt%	σ
O	47.7	0.4
Ca	30.2	0.2
Si	5.8	0.1
Mg	4.2	0.1
K	2.9	0.1
Al	2.5	0.1
Fe	1.5	0.1
Mn	1.5	0.1
S	1.4	0.1
P	1.4	0.1
Na	0.5	0.1
Cl	0.5	0.0

Figure 2: Chemical elements for one sample of wood ash burned at 850 degrees Celsius

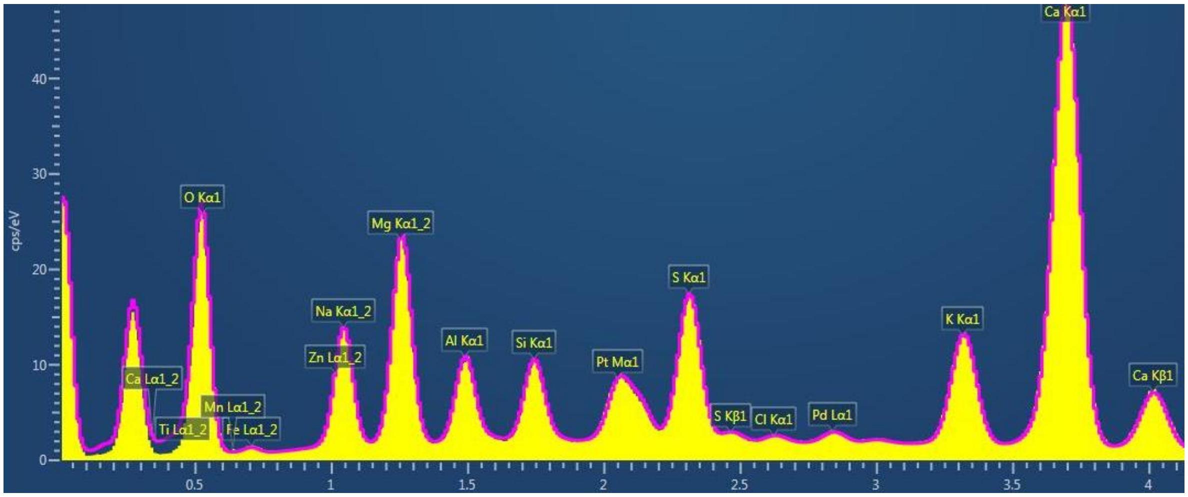


Figure 3: Chemical elements for one sample of wood ash burned at 1000 degrees Celsius

Table 2: Average composition of chemical elements for wood ash burned at 700 degrees Celsius (%)

Statistics	O	F	Na	Mg	Al	Si	P	S	Cl	K	Ca	Mn	Fe	Zn	Zr	Pd
Max	49.5	0.57	13.24	8.18	5.3	13.3	1.97	4.99	5.71	5.14	32.2	2.71	2.2	0.57	7.04	2.09
Min	34.42	0.52	4.42	0.98	1.52	1.67	1.97	1.2	0.3	1.25	12.2	0.35	0.4	0.26	3.22	0.71
Average	44.09	0.55	8.83	4.58	3.41	7.49	1.97	3.1	3.01	3.2	22.2	1.53	1.3	0.42	5.13	1.4
Standard Deviation	7.3	n.d.	3.13	2.37	1.46	4.34	n.d.	1.63	n.d.	1.49	7.58	0.94	0.6	n.d.	n.d.	n.d.

n.d. – not determined

Table 3: Weight % of elements for wood ash burned at 850 degrees Celsius

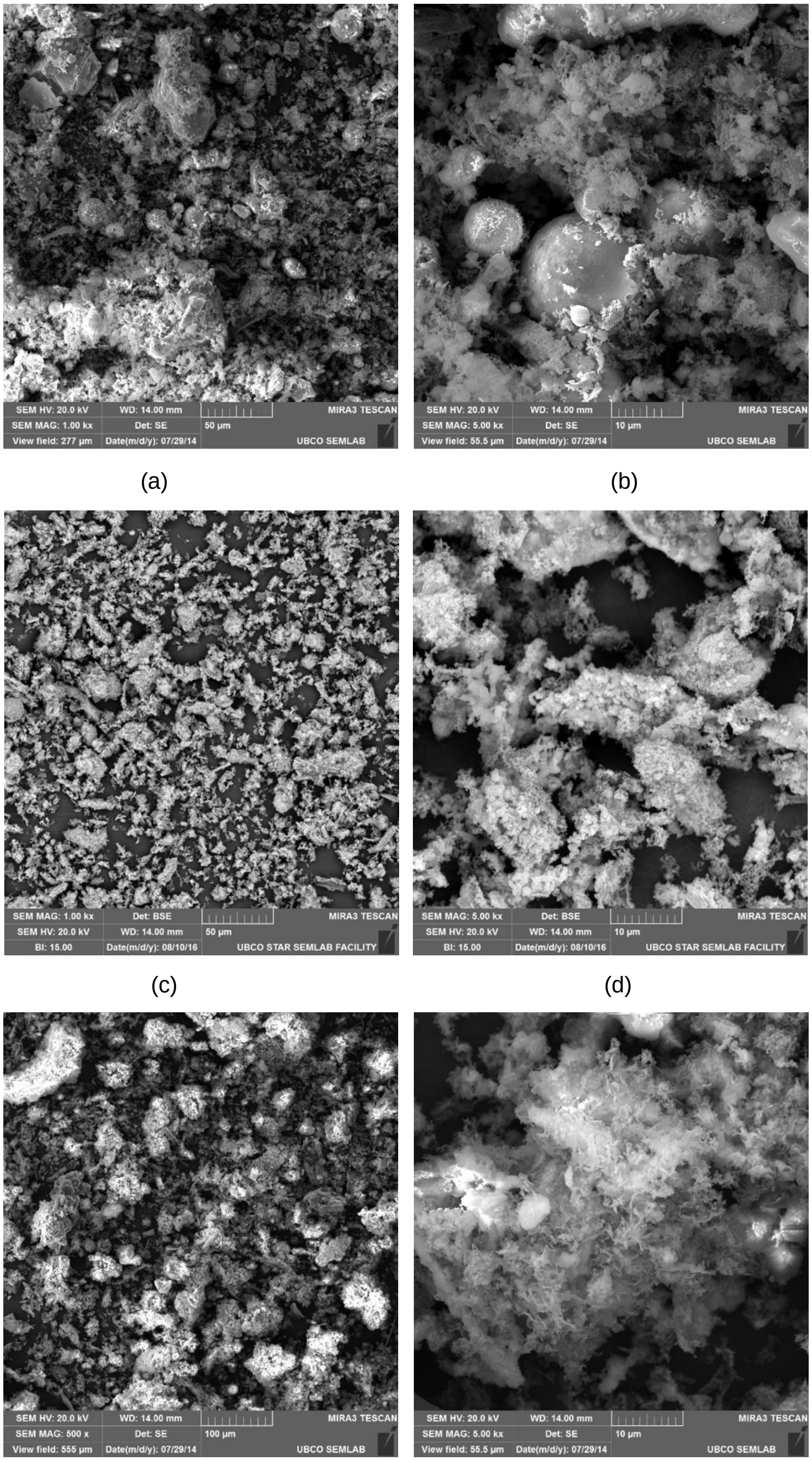
Statistics	O	Na	Mg	Al	Si	P	S	Cl	K	Ca	Mn	Fe	Zr	Ba
Max	60.55	0.74	6.69	6.34	24	5.63	1.53	0.62	9.2	45.9	3.42	3.89	3.15	0.92
Min	42.36	0.3	0.75	0.9	1.41	0.68	0.3	0.21	0.35	13.3	0.37	0.2	2.27	0.54
Average	53.68	0.37	4.33	2.46	4.94	1.38	0.89	0.41	1.4	28	1.18	1.05	1.14	0.73
Standard Deviation	4.83	n.d.	1.21	0.97	4.29	n.d.	n.d.	n.d.	1.78	6.05	0.6	0.7	n.d.	n.d.

n.d.- not determined

Table 4: Weight % of elements for wood ash burned at 1000 degrees Celsius

Statistics	O	Na	Mg	Al	Si	S	Cl	K	Ca	Ti	Mn	Fe	Zn	Zr	Pd	Ir
Max	53.62	17.7	16.4	3.31	10.4	4.65	0.43	4.7	30.79	0.23	7.62	4.62	0.75	4.29	1.05	1.86
Min	41.94	2.77	1.8	0.45	2.46	0.18	0.11	0.28	12.11	0.21	0.4	0.49	0.29	2.77	0.7	0.74
Average	46.77	7.24	6.93	2.56	5.46	2.42	0.27	2.49	21.45	0.22	4.01	2.555	0.52	3.53	0.88	1.3
Standard Deviation	3.73	4.13	4.44	0.93	2.8	n.d.	n.d.	1.68	5.49	n.d.	2.26	1.24	n.d.	n.d.	n.d.	n.d.

n.d.- not determined



(a) (b)

(c) (d)

(e) (f)

Figure 4: Wood ash at different magnifications

(a) 700 degrees at 1000x’s (b) 700 degrees at 5000x’s (c) 850 degrees at 1000x’s
(d) 850 degrees at 5000x’s (e) 1000 degrees at 1000x’s (f) 1000 degrees at 5000x’s

As expected the samples contained Si, Ca, Al, Se, Na and Mg in addition to traces of other elements (Tables 2, 3 and 4). It was noted that the weight of the chemical elements did not vary significantly with temperature change (Figure 3, Tables 2, 3 and 4). This suggests that the increase in temperature may have changed the chemical compounds as evident from the compression tests discussed in Section 3.2. Due to the measureable differences between treating ash at 700ºC to 850ºC or 1000ºC indicates a chemical reaction occurring within this range, and further chemical analysis is recommended for future research purposes.

3.2 Compressive Strength

The compressive strength results of the average three mortar cube tests are shown in Table 5. The percentage difference shows the deviation with each temperature group and waste wood ash (WWA) replacement level with that of the control groups. Control (1) was used to compare with samples at 700ºC and 1000ºC whereas Control (2) was used to compare with samples treated at 850ºC.

After analysing the compressive strength of wood ash for each temperature group, fairly similar patterns can be seen with the level of cement replaced. When replacing cement with 10% wood ash, the compressive strength decreased by 4% at 3 days and 6.5% at 29 days for samples heat treated at 700ºC. After increasing the treated wood ash to 20% and 30% replacement, the compressive strength significantly decreased, yielding a negative percentage difference for the entire 700ºC group. On the other hand, when treated WWA was used at 850ºC, an increase in strength of 32.2% and 17.6% for replacement levels of 10% and 20% respectively was observed at 7 days. However, by 29 days a decrease in strength was noted for all levels of replacement. Overall, the 850ºC group showed a 16.1% increase with 10% replacement, and an acceptable level at 20% replacement with a decrease of only 1.1% in strength. For samples with WWA treated at 1000ºC, the compressive strength with 10% replacement increased by 15% at 29 days. With 20% replacement, the strength was also very similar to that of the control, however, there was a large reduction in strength with an increase to 30% replacement. The outcomes of this study yield that when treated at 850ºC or 1000ºC the wood ash showed promising results for replacements between 10% and 20%. For the purpose of sustainability, treating the wood ash at 850ºC with 20% replacement is the optimal temperature and cement replacement without effecting the compressive strength.

Table 5: Compressive strength for mortar cubes

Mix name	Compressive strength (MPa)			Percentage difference* (%)		
	3 days	7 days	29 days	3 days	7 days	29 days
Control (1)	28.9	32.3	38.3	0.0	0.0	0.0
Control (2)	20.3	27.1	38.4	0.0	0.0	0.0
W10-T700	27.7	30.7	35.8	-4.0	-5.0	-6.5
W20-T700	18.2	21.7	24.6	-37.0	-32.9	-35.8
W30-T700	11.6	20.2	27.9	-59.8	-37.4	-27.1
W10-T850	26.3	35.8	44.6	29.8	32.2	16.1
W20-T850	22.9	31.9	38.0	13.2	17.6	-1.1
W30-T850	20.5	25.8	32.5	1.2	-4.6	-15.4
W10-T1000	30.3	34.4	44.2	5.0	6.3	15.5
W20-T1000	29.7	33.3	39.3	2.8	2.9	2.6
W30-T1000	13.4	26.0	30.8	-53.5	-19.5	-19.6

*Relative to Control (1) for 700 ºC and 1000 ºC and to Control (2) for 850 ºC

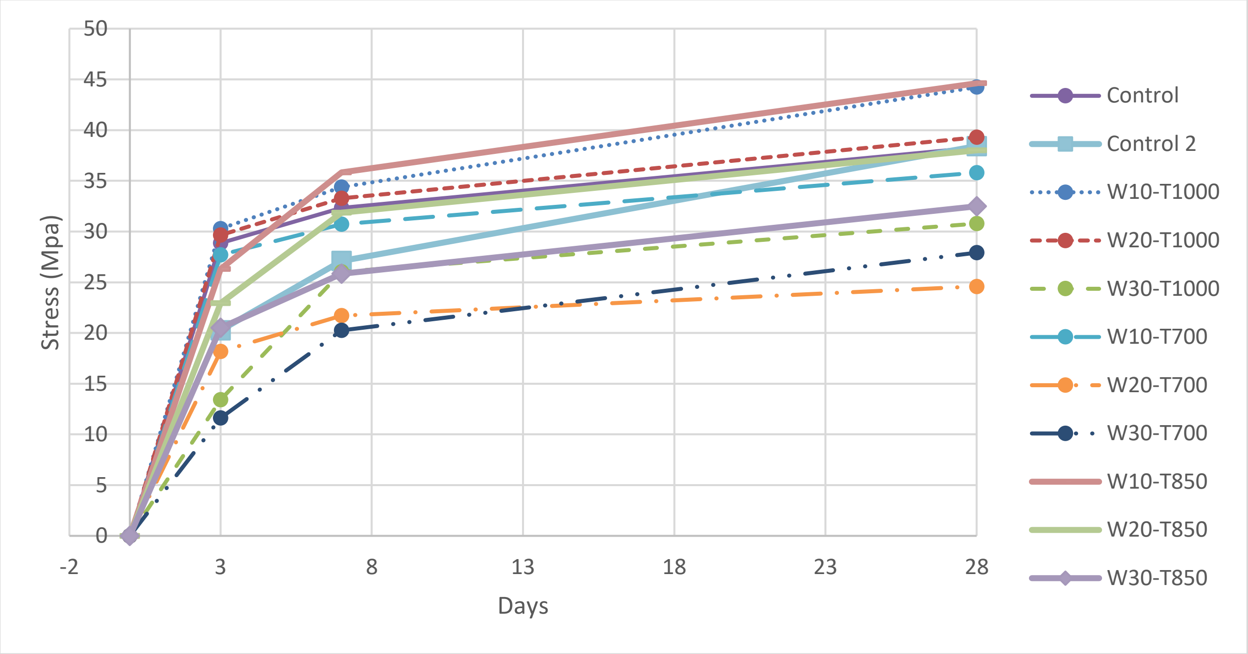


Figure 5: Compressive strength gain of mortar cubes.

4 CONCLUSIONS

An experimental program was developed to determine the effect of waste wood ash as a partial cement replacement on the compressive strength of mortar cubes. The percentage replaced and temperature of kiln were the parameters analyzed. Based on the results obtained, the following conclusions can be drawn:

- The mortar cubes' compressive strength typically decreased with an increase in the ash content.
- At each percentage level (10, 20 and 30%) and curing period, the samples treated at 850 and 1000 degrees outperformed their 700 degree counterpart, the temperature of the kiln clearly affects the compressive strength.
- The samples replaced at 10% with a kiln temperature of 850 degrees outperformed the control (2) mix at 7 days by 32% and at 29 days by 16%.
- The 10% and 20% replacement at 1000 degrees both outperformed the compressive strength of the control mix at 7 days, by 6% and 3% respectively, and at 29 days, by 16% and 3% respectively.
- The 10% replacement at 700 degrees showed acceptable strength results at 7 and 28 days with 95 and 94 percent of the control, respectively.
- Samples treated at 30% replacement demonstrated the lowest results at all three temperatures, however at 850 degrees showed acceptable strength at 7 days with 94 percent of the control.
- 20% replacement at 850 degrees Celsius is the optimal percentage replacement and temperature treatment from this study.

ACKNOWLEDGMENTS

The authors would like to thank Mr. Kyle Stratton, Mr. Trevor Billows and Mr. Devin Walline for their assistance in the research experiments.

5 Bibliography

Barathan, S., & Gobinath, B. (2013). Evaluation of wood ash as a partial replacement to cement. *International Journal of Science, 2*(10), 2009-2013.

Cheah, C. B., & Ramli, M. (2011). The implementation of wood waste ash as a partial cement replacement material in the production of structural grade concrete and mortar: An overview. . *Resources, Conservation and Recycling, 55*, 669-685.

CSA-A3004. (2013). Test methods and standard practices for cementitious materials for use in concrete and masonry.

Elinwa, A. U., & Mahmood, Y. A. (2002). Ash from timber waste as cement replacement material. *Cement and Concrete Composites, 24*, 219-222.

Humphreys, K., & Mahasenen, M. (2002). Climate Change. *Towards a Sustainable Cement Industry: Substudy 8*, 1-92.

Misra, M. K., Ragland, K. W., & Baker, A. J. (1993). Wood ash composition as a function of furnace temperature. *Biomass and Bioenergy, 4*(2), 103-116.

Ramos, T., Matos, A. M., & Sousa-Coutinho, J. (2013). Mortar with wood waste ash: Mechanical strength carbonation resistance and ASR expansion. *Construction and Building Materials, 49*, 343-351.

Siddique, R. (2012). Utilization of wood ash in concrete manufacturing. *Resources, Conservation & Recycling, 67*, 27-33.