Journal of Materials Science and Chemical Engineering, 2016, 4, 101-114
Published Online July 2016 in SciRes. http://www.scirp.org/journal/msce
http://dx.doi.org/10.4236/msce.2016.47013

Effects of Wood Ash on Properties of Concrete and Flowable Fill

Zhifu Yang, Jon Huddleston, Heather Brown

Department of Concrete Industry Management, Middle Tennessee State University, Murfreesboro, TN, USA
Email: zyang@mtsu.edu

Received 1 June 2016; accepted 27 July 2016; published 29 July 2016

Abstract

This research investigated the use of wood ash to partially replace cement or sand in conventional concrete, roller compacted concrete (RCC), and flowable fill. The main focus was to determine how the wood ash addition affected the main fresh and hardened properties of these materials. It was found that the wood ash could be successfully incorporated into the conventional concrete. In particular, the wood ash addition not only accelerated the setting, but also improved the early and the 28-day compressive strength of concrete that contained the blast furnace slag. It was also observed that the wood ash could be positively added into RCC to facilitate the compaction and reduce the risk of segregation. In addition, the wood ash can be beneficially introduced into the flowable fill mixtures to facilitate flow, to alleviate bleeding and subsidence, as well as to achieve controlled strength especially when combined with the class C or the class F fly ash.

Keywords

Wood Ash, Conventional Concrete, Roller Compacted Concrete, Flowable Fill, Setting, Workability, Compressive Strength

1. Introduction

The widespread use of biomass fuel in the Oak Ridge National Laboratory Biomass Plant has produced approximately 100 tons of wood ash every day. Commonly, the wood ash is disposed through landfilling; however, the potential risk of airborne particles and ground water contamination requires a well-designed and prepared landfill site, leading to high cost. Moreover, the concern of landfilling is growing due to less availability of space and more strict environmental regulations. As a result, new and more economical solutions are essential for disposing the wood ash over the long run.

One of the beneficial applications is to incorporate the wood ash into flowable fill. Early documented research occurred in 1996 when Fehrs [1] investigated the flowability and the strength development of flowable fill that used wood ash as a major ingredient material. It was reported that the wood ash was suitable for flowable fill applications. More recently, Naik *et al.* [2]-[5] studied the effects of wood ash on the fresh and hardened properties of flowable fill and concluded that the wood ash could be successfully used in flowable fill. Another beneficial application is to use the wood ash as a cement replacement, a mineral admixture, or an aggregate filler in concrete. Various studies have been conducted to evaluate the influence of wood ash additions on concrete

How to cite this paper: Yang, Z.F., Huddleston, J. and Brown, H. (2016) Effects of Wood Ash on Properties of Concrete and Flowable Fill. *Journal of Materials Science and Chemical Engineering*, **4**, 101-114.
http://dx.doi.org/10.4236/msce.2016.47013

properties. For example, Ban and Ramli [6] studied the utilization of wood ash to partially replace cement in structural concrete and concluded that the wood ash increased the water demand and reduced the mechanical strength of concrete; while there were insignificant effects on the durability and a noticeable reduction in the dry shrinkage. Similarly, Udoeyo *et al.* [7] investigated the addition of wood waste ash to the concrete up to 30% by the weight of cement and a remarkable reduction (by 9% to 38%) in the mechanical strength was noted especially for mixtures that incorporated high levels of wood ash. Also, Rajamma *et al.* [8] performed research on the use of two wood ashes in cement-based materials. It was found that the hydration rate and the product formation greatly depended on the alkali content and the water-to-binder ratio of mixtures. Again, the wood ash concrete exhibited the higher water demand and the lower mechanical strength. However, a slight increase in the rate of hydration and a reduced setting time were observed. In addition, Wang *et al*. [9]-[11] conducted a comprehensive study on the effects of biomass fly ash on the mixture proportioning, mechanical strength, and durability of concrete. It was found that the use of wood ash to partially replace cement in concrete substantially increased the water demand, the setting time, and the required dosage of air-entraining admixtures as well as compromised the long-term strength of concrete. However, it had small impacts on the early age compressive strength, chloride penetration, and freeze and thaw durability. More diverse applications of wood ash may include agricultural soil improvement [12] [13], road base, and masonry products.

This study was to identify the potentials of using wood ash from the Oak Ridge National Laboratory Biomass Plant in conventional concretes, particularly in those blended with blast furnace slag and silica fume. This study was also to investigate the suitability of wood ash for Roller Compacted Concrete (RCC) as well as flowable fill applications.

2. Experimental Programs

2.1. Characterization of Wood Ash

Prior to use, the coarse particles in wood ash larger than 0.6 mm, which were primarily unburned carbon, were removed by sieving. **Figure 1** illustrates the sieved wood ash sample used in this study. ASTM C136 [14] was used to analyze the particle size and gradation of wood ash and the result is summarized in **Table 1**. The specific gravity of wood ash was 2.37 based on ASTM C188 [15]. The loss on ignition was 6.7%, which was examined following the procedure similar to the one described in ASTM C114 [16]. The chemical compositions of wood ash included approximately 5.8% of SiO_2, 45.7% of CaO, 9.1% of MgO, 20.8% of K_2O, and 11.9% of other oxides (all by weight).

2.2. Materials, Proportioning, and Test Procedures

2.2.1. Conventional Concrete

The materials used in conventional concrete mainly included type I Portland cement, grounded granular blast furnace slag/silica fume, crushed limestone, river sand, and wood ash. The basic proportion (the control mixture) by weight was water: cementitious materials: crushed limestone: river sand = 0.42:1:2.85:2.37. Three levels of wood ash (10%, 20%, and 30% by weight of cement) were used in this study to partially replace the cement or

Figure 1. Wood ash sample used in this study.

Table 1. Gradation of wood ash in this study.

Sieve No.	Sieve Opening, mm	Percent Passing, %
#30	0.6	100
#50	0.3	74.4
#100	0.15	55.3
#200	0.075	38.3
Pan	0	0.00

as an addition. The same quantity of sand was reduced when the wood ash was introduced as an addition. The blast furnace slag was provided by Holcim (US) Inc. with a Blaine Fineness of 579 m^2/kg and an average slag activity index of 120% (at 28 days). The dosage of slag was 40% by weight of cement, which was added into some concrete mixtures to partially replace cement. A compact silica fume was provided by BASF with a SiO_2 content of 95%, a specific surface area of 30,000 m^2/kg, and a specific gravity of 2.22. A typical dosage of silica fume was 10% by weight of cement, which was also added into some mixtures as a partial replacement of cement. The crushed limestone had a nominal maximum size of 9.5 mm, a specific gravity (SSD) of 2.7, and absorption of 1.2%. Natural river sand had a specific gravity of 2.68 and absorption of 0.56%. A High-Range Water Reducer (HRWR-Glenium 7500 from BASF) was used in the silica fume concrete with wood ash as an addition and the typical dosage was 0.78 ml per 100 kg of cement. An Air-Entraining Admixture (AEA-Micro-air from BASF) was employed in some mixtures to evaluate the effects of wood ash additions on air entrainment of concrete and the dosage was 1.63 ml per 100 kg of cement. All materials were mixed in a 0.17 m^3 rotating drum mixer, following the procedures described in ASTM C192 [17] with a typical batch size of approximately 0.085 m^3.

The slump, unit weight, and air content of fresh concrete were measured following ASTM C143 [18], ASTM C138/C138M-01a [19] and ASTM C231 [20]. The time of setting of concrete was evaluated based on the pin penetration test (ASTM C403 [21]). The unrestrained dry shrinkage of concrete was examined following the procedures in ASTM C157 [22]. The compressive strength was determined at different time intervals (e.g. 1 day, 7 days, and 28 days) following ASTM C 39 [23] using SATEC SYSTEMS Model 5500 supplied by INSTRON. A load control mode was used at a loading rate of 0.24 MPa/s. After mixing, the fresh concrete was placed into 101.6 × 203.2 mm cylindrical plastic molds and externally vibrated for approximately 15 seconds. The specimens were subsequently finished, capped, stored at the room temperature (approximately 23˚C) for approximately 24 hours, and then demolded and cured in the lime-saturated water at 23˚C until the time of testing.

2.2.2. Roller Compacted Concrete (RCC)

The materials used in RCC mainly included type I Portland cement, crushed limestone, river sand and wood ash. The basic proportion (the control mixture) by weight was water: cement: crushed limestone: sand = 0.36:1:4:3. Three levels of wood ash (10%, 20%, and 30% by the weight of cement) were incorporated into the RCC mixtures to partially replace the cement or as an addition (*i.e.* aggregate filler).When the wood ash was used as an addition, the sand was reduced by the same weight to avoid the excessive fines in the mixture. A 0.17 m^3 rotating drum mixer was employed for mixing and a typical batch size was approximately 0.085 m^3. The consistency and the density of RCC were determined following the procedure A in ASTM C1170 [24], in which the Vebe time was measured to indicate the consistency of RCC. Shorter Vebe time implied more workable RCC. The compressive strength of RCC was assessed following ASTM C39 using 152.4 × 304.8 mm cylindrical specimens. The specimens were prepared based on the procedures described in ASTM C1176 [25]. After finishing, the specimen was covered with plastic sheets, and cured at approximately 23˚C for 24 hours. After the initial curing, the specimen was demolded and cured in the lime-saturated water at 23˚C until the time of testing.

2.2.3. Flowable Fill

The materials used in flowable fill included type I Portland cement, class C/F fly ash, natural river sand, and wood ash. The class C fly ash was provided by Holcim (US) Inc. and the class F fly ash was supplied by the SEFA group. All materials were mixed in a 0.17 m^3 rotating drum mixer with a typical batch size of approximately 59 kg. The flowability test was performed following ASTM D6103 [26]. The bleeding and subsidence of fresh flowable fill were measured using 152.4 × 304.8 mm cylindrical plastic containers. After mixing, the fresh flowable fill was placed into the container and seated on the lab floor. The bleeding water accumulated on the top was extracted and weighed every 20 minutes until the bleeding stopped. The total weight of extracted water was used as an indication of bleeding. The distance between the top of the container and the top surface of flowable fill was taken at the time when the bleeding stopped, which was used to represent subsidence. The compressive strength was measured at 7 days and 28 days respectively to evaluate the strength development of flowable fill. After mixing, the fresh flowable fill was placed into 76.2 × 152.4 mm cylindrical paper molds that were specially designed for easy stripping. The specimen was then finished with a steel trowel, covered with plastic sheets, and cured in air at 23˚C and 60% relatively humidity for approximately 24 hours. After the initial curing, the specimen was stripped, sealed in a plastic bag, and stored in an environmental chamber at 23˚C and 60% relative humidity until the time of testing. The unconfined compressive testing was performed using Proving Ring Device (Model 5510) with a capacity of 4540 kg from KAROL WARNER Soil Testing Systems. A displacement-controlled mode at a rate of 0.5 mm/min. was used and the peak load of each specimen was recorded during the test. Three specimens were tested for each mixture and the unconfined compressive strength of each mixture was calculated by dividing the average peak load of three specimens by the cross sectional area of the cylinder.

3. Results and Analyses

3.1. Effects of Wood Ash on Properties of Conventional Concrete

3.1.1. Slump, Unit Weight, and Fresh Air Content

The slump, unit weight, and air content of fresh concrete using wood ash as a partial replacement of cement or as an additional fine material are summarized in **Table 2**. It can be seen that the use of wood ash to partially replace cement (#2, #3, and #4) slightly reduced the slump (by less than 50.8 mm) as well as the unit weight (by less than 64.1 kg/m^3) of concrete as compared with the control mixture#1. The small reduction in slump may be ascribed to the high unburned carbon in wood ash that absorbed water, which reduced the free water content in the mixture. The decrease in unit weight was due to the fact that the wood ash was lighter than cement. It can also be seen that the effect of wood ash on the fresh air content was insignificant. This fresh air was primarily the entrapped air because no air-entraining admixtures were used in these mixtures. As a contrast, the wood ash addition slightly reduced the unit weight of concrete (#5, #6, and #7), but there was no clear trend for the entrapped air content. In addition, a small increase in the slump was noticed for the low wood ash addition (e.g., 10%); whereas at relatively high wood ash additions (e.g., 20% or 30%), the slump decreased significantly. One explanation was that the wood ash was coarser than cement, but finer than sand. Adding wood ash would fill the gap between the cement and the sand, leading to a better gradation of the mixture and thus a more workable concrete. That was why a 10% wood ash addition increased the slump/workability of concrete. However, once wood ash exceeded the optimal level, more wood ash particles would negatively impact the gradation of mixture, leading to a less workable concrete. That was why at high wood ash additions (20% and 30%), the slump of concrete significantly decreased. Another reason that contributed to the reduction of slump was that finer wood ash particles particularly with high unburned carbon, when used as an addition (*i.e.*, a partial replacement of sand), would excessively absorb and adsorb water, thus reducing the free water availability in the mixture.

The effect of wood ash on the fresh properties of concrete blended with blast furnace slag is also shown in **Table 2**. In this series of tests, 40%of cement by weight was blended with slag (#8). Then, 10% to 30% wood ash (by weight of cement in the control mixture #1) was added to further replace the cement (#9, #10, and #11) or as additional fine materials (#12, #13, and #14). It can be seen that the 10% wood ash replacement (#9) significantly increased the slump of concrete by 63.5mm and the 10% wood ash addition (#12) resulted in a small increase in slump (12.7 mm). This can be again ascribed to the improvement in the gradation of mixture as a result of 10% wood ash replacement or addition. However, at high dosages of wood ash replacement (20% and 30%), the slump was seen to decrease. In particular, significant drop in slump was observed for concretes with high dosages of wood ash additions (#13 and #14). This was again because introducing high percentages of wood ash caused excessive fines and high unburned carbon in the mixture, which would cause poor gradation as well as reduce free water availability. In addition, the wood ash replacement or addition slightly reduced the unit weight of concrete and slightly increased the entrapped air content. The influence of wood ash on the fresh

Table 2. Properties of various fresh concrete mixtures with wood ash (WA).

Mixture ID	Slump, mm	Unit Weight, kg/m^3	Air Content, %
#1 (Control)	127	2390.9	1.5
#2 (10%WA replacement)	108	2378.1	1.6
#3 (20%WA replacement)	108	2371.7	1.3
#4 (30%WA replacement)	101.6	2326.8	1.5
#5 (10%WA addition)	139.7	2371.7	1.2
#6 (20%WA addition)	76.2	2358.9	1.8
#7 (30%WA addition)	25.4	2365.3	1.5
#8 (slag + 0% WA)	152.4	2397.3	1.6
#9 (slag + 10%WA replacement)	215.9	2371.7	0.8
#10 (slag + 20%WA replacement)	133.4	2339.7	1.2
#11 (slag + 30%WA replacement)	139.7	2346.1	1.2
#12 (slag + 10%WA addition)	165.1	2365.3	1.3
#13 (slag + 20%WA addition)	82.6	2358.9	1.6
#14 (slag + 30%WA addition)	50.8	2339.7	1.7
#15 (SF + 0%WA)	12.7	2378.1	2.8
#16 (SF + 10%WA replacement)	19.1	2301.2	2.0
#17 (SF + 20%WA replacement)	19.1	2275.6	2.4
#18 (SF + 30%WA replacement)	25.4	2333.2	1.9
#19 (SF + HRWR+ 0%WA)	101.6	2326.8	2
#20 (SF + HRWR + 10%WA addition)	88.9	2346.1	1.5
#21 (SF + 2HRWR + 20%WA addition)	44.5	2326.8	2.2
#22 (SF + 3HRWR + 30%WA addition)	31.8	2307.6	2.5
#23 (AEA + 0%WA)	127	2353.8	6.3
#24 (AEA + 10%WA addition)	76.2	2205	4
#25 (AEA + 20%WA addition)	88.9	2314	3.4
#26 (AEA + 30%WA addition)	25.4	2371.7	2.7

properties of concrete blended with silica fume was also evaluated in this study and the results are summarized in **Table 2**. 10% of cement by weight was substituted with silica fume (#15). Adding 10% to 30% wood ash (by weight of cement in the control mixture #1) to further replace cement (#16 to #18) roughly increased the slump of concrete by 6.35 to 12.7 mm. The effects of wood ash on the slump may be again attributed to the particle size and gradation of wood ash. Introducing 10% wood ash aided in improving the combined gradation; while excessive wood ash (20% to 30%) resulted in the poor combined gradation. In addition, the effect of wood ash addition on the efficiency of High-Range Water Reducer (HRWR) can be assessed in this study (#19 to #22). It can be seen that the wood ash addition substantially increased the demand for HRWR. For example, a 30% wood ash addition (#19) increased the demand by more than 3 times to attain a workable concrete. This was again because unburned carbon in wood ash absorbed HRWR, making it unavailable for the improvement of workability. The wood ash addition slightly reduced the unit weight of silica fume concrete. However, its effect on entrapped air contents differed from batch to batch. It seemed that replacing the cement partially with wood ash was likely to reduce the entrapped air content, but the use of wood ash as an addition would possibly increase the air entrapment. One plausible explanation was that silica fume concrete itself was sticky, which was more susceptible to entrap air. The use of coarse wood ash to replace finer cement would reduce the stickiness of the mixture, thus reducing the air entrapment. Oppositely, the use of wood ash to replace coarser sand (*i.e.*, wood ash as an addition) would increase the stickiness of mixture, which could entrap more air bubbles. The wood ash addition in concrete had great impacts on the effectiveness of Air-Entraining Admixture (AEA). Table 2 presents the results of how wood ash affected the air entrainment of concrete (#23 - #26). It can be seen that at the same dosage of AEA, an increase in the wood ash addition resulted in a lowered entrained air content in concrete, indicating that wood ash reduced the effectiveness of AEA. This was again due to the high unburned carbon in wood ash, which would absorb AEA, thus making it unavailable for air entrainment.

3.1.2. Time of Setting

Figure 2 compares the results of conventional concrete mixtures that incorporated various percentages of wood ash. In general, the use of wood ash as a replacement of cement (**Figure 2(a)**) slowed down the setting of concrete. Specifically, a 30% wood ash replacement was found to exhibit the slowest setting followed by 10% and then 20%. This was because the setting of concrete was primarily controlled by Tri-Calcium-Aluminates (C_3A) and Sulfate in the pore solution of fresh concrete. The wood ash that did not contain C_3A, when replacing cement, reduced the concentration of C_3A in the pore solution, causing slower setting of concrete.

When the wood ash was incorporated as an addition (or replacement of sand), two opposite effects on the time of setting were observed (**Figure 2(b)**). The concrete with 10% wood ash addition (#5) showed faster setting than the control mixture (#1). However, the concrete with20% wood ash addition (#6) displayed almost 3 hours delay and the concrete with 30% wood ash addition(#7) demonstrated nearly 2 hours delay as compared with the control mixture (#1). Although the exact mechanism for these conflicting results was not clear, a plausible explanation was that the wood ash contained a high amount of calcium oxide and alkali (sodium and potassium oxides). At the 10% wood ash addition, the alkali in wood ash were likely to promote the solubility of aluminate/silicate ions of cement particles into the pore solution, thus accelerating the setting of concrete [27]. However, at the 20% and 30% wood ash additions, the alkali in the pore solution became so high, which could depress the dissolution of Ca^{2+} into the pore solution, thus decelerating the hydration reaction and the setting of concrete [27].

The use of wood ash in the concrete mixtures blended with 40% slag also affected the time of setting of concrete as illustrated in **Figure 3**. Overall, the wood ash replacement or addition decelerated the setting of concrete. The use of wood ash as a partial replacement of cement from 10% to 30% (#9 to #11) approximately prolonged the setting time by 1.5 to 2 hours as compared with the concrete without wood ash replacement (#8) (**Figure 3(a)**). This was again because the use of wood ash to replace cement reduced the concentration of aluminates in the mixture. More wood ash replacement led to more reduction in aluminate concentration and consequently

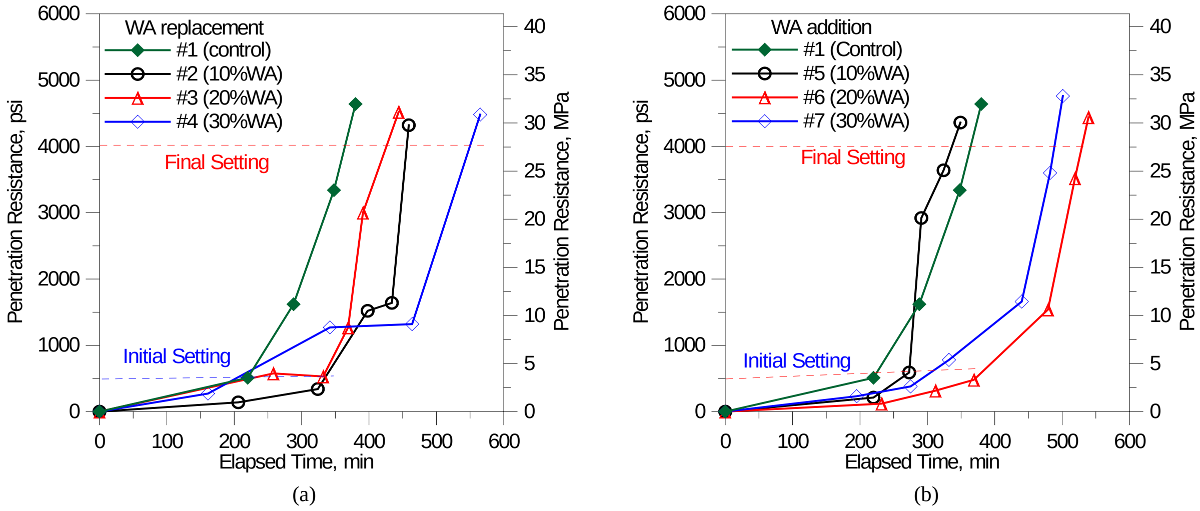


Figure 2. Effects of wood ash on time of setting of conventional concrete.

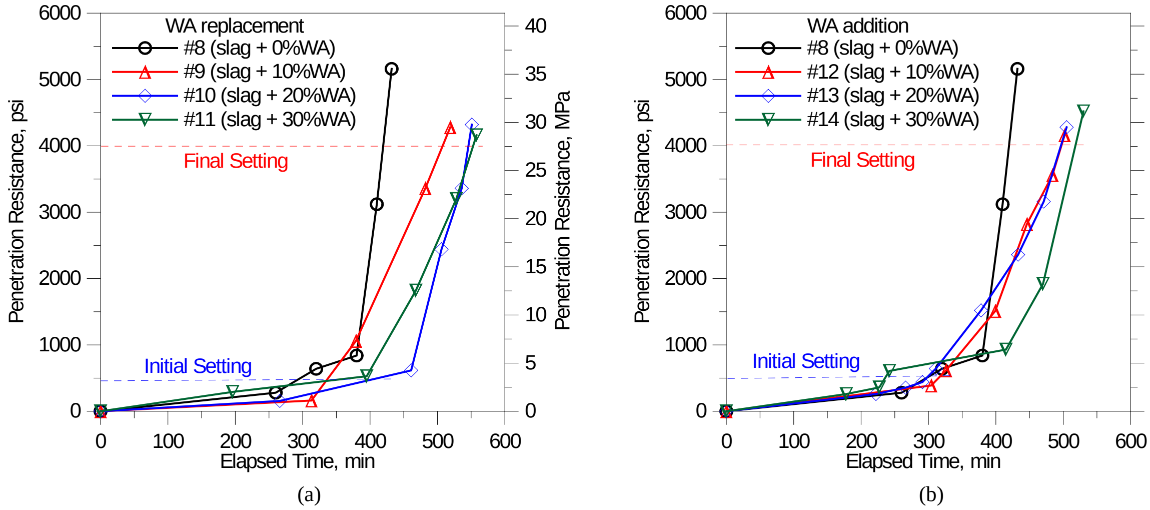


Figure 3. Effects of wood ash on time of setting of concrete blended with 40% slag.

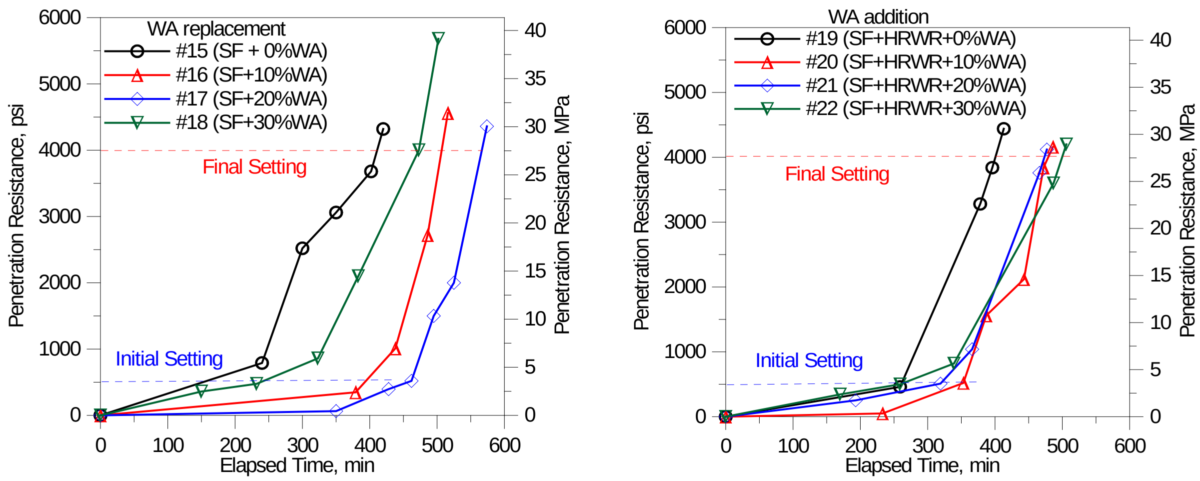
slower setting. When the wood ash was introduced as an addition (#12 to #14), the setting of concrete was delayed by approximately 1.5 hours (**Figure 3(b)**). Although wood ash addition did not reduce the aluminate content in the pore solution, the high alkali content in wood ash was likely to excessively accelerate the hydration reaction of aluminates at the very early age, which resulted in insufficient calcium ions in the pore solution due to the fact that they were excessively consumed in the early aluminate hydration. The lack of calcium in the solution would depress the hydration reaction of silicates causing retardation of concrete mixtures [28]. This is particularly true when the 30% wood ash was added (#14 in **Figure 3(b)**), which displayed the fastest initial setting, but the slowest final setting. This indicated that a high percentage wood ash addition was able to accelerate the hydration reaction at the very early age (primarily aluminate reaction), but the hydration reaction after a few hours after the water was added (primarily silicate reaction) was retarded [28].

The setting time of concrete that contained a combination of 10% silica fume and various dosages of wood ash was illustrated in **Figure 4**. Similarly, introducing wood ash into the silica fume concrete to partially replace cement generally retarded the setting of concrete (#15 to #18 in **Figure 4(a)**). This was again because the wood ash replacement reduced the C_3A content. However, the retardation effects of wood ash depended on the dosage and the way of using wood ash in concrete. For example, the concrete with a 30% wood ash replacement (#18) exhibited slower setting than the concrete without wood ash replacement (#15), but it demonstrated faster setting than those with 10% (#16) and 20% (#17) wood ash replacements. This may be due to the combined effect of alkaliand silica fume in the mixture. The wood ash addition also slowed down the setting of concrete (#19 to #22 in **Figure 4(b)**); however, it seemed that the three concrete mixtures with 10% to 30% wood ash additions showed similar trends.

3.1.3. Compressive Strength Development

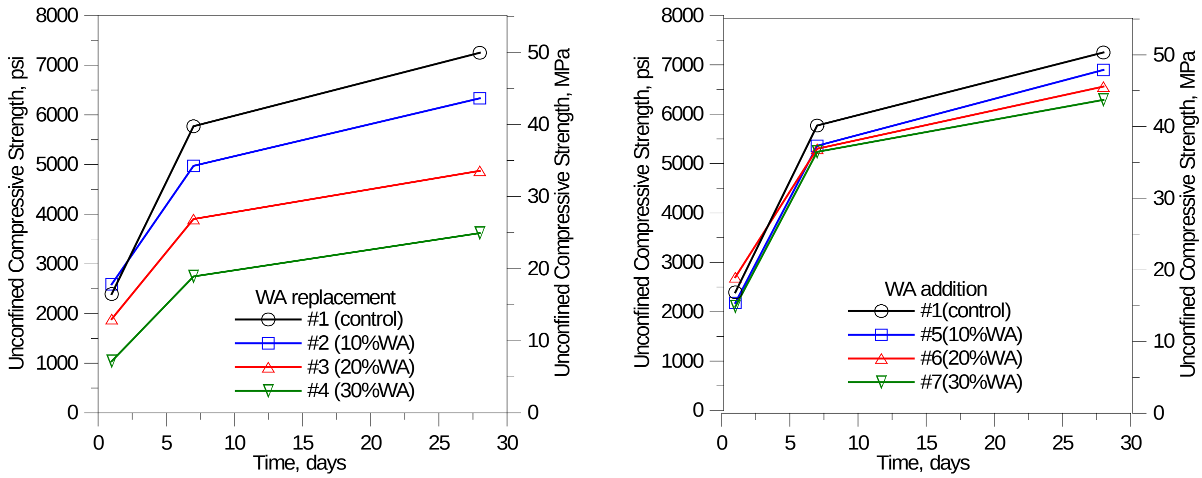
The compressive strength development of concrete mixtures comprising different percentages of wood ash is shown in **Figure 5**. Overall, the use of wood ash to partially replace cement (**Figure 5(a)**) reduced both the early-age and the 28-day compressive strength of concrete. It appeared that higher wood ash replacement would result in lower compressive strength of concrete. The primary reason was that the wood ash was neither self-cementing, nor pozzolanic. The use of wood ash to replace cement reduced the cementitious material content in the mixture, causing a lower compressive strength. A slight increase in the 1-day compressive strength of concrete with the 10% wood ash replacement may be associated with alkali in wood ash that promoted the early hydration reaction. However, at high wood ash replacements (20% or 30%), the negative effects of cement reduction became dominant, which resulted in a decrease in the compressive strength of concrete even at the very early age.

In contrast, the use of wood ash as an addition had small impacts on the compressive strength development especially at the early age as shown in **Figure 5(b)** (#5 to #7). Although the wood ash addition did not influence the 1-day compressive strength significantly; it slightly lowered the 7-day compressive strength and perceptibly



(a) (b)

Figure 4. Effects of wood ash on time of setting of concrete blended with 10% silica fume.



(a) (b)

Figure 5. Effects of wood ash on compressive strength development of concrete.

reduced the 28-day compressive strength. It seemed that a higher wood ash addition would cause more reduction in the 28-day compressive strength. Although the use of wood ash as an addition did not reduce the cementitious material content in concrete, the presence of unburned carbon would create weak spots that facilitated cracking during loading. The stronger the concrete, the more obvious its effect would be. As a result, a slight decrease in the 7-day compressive strength, but a more noticeable reduction in the 28-days compressive strength could occur. The effects of wood ash on the compressive strength development of concrete blended with 40% slag are presented in **Figure 6**. It is commonly recognized that the use of slag to partially substitute cement reduces the early-age compressive strength of concrete. This was further confirmed by this study, in which the slag decelerated the early compressive strength development of concrete (**Figure 6(a)** vs. **Figure 5(a)**). Furthermore, the use of wood ash to replace cement led to an additional decrease in the compressive strength. A higher percentage of wood ash replacement resulted in even lower compressive strength. This was again due to the reduced cementitious material content in the mixture.

Oppositely, the use of wood ash as an addition in concretes blended with 40% slag significantly increased their compressive strength (**Figure 6(b)**). For all concrete mixtures with wood ash additions (10%, 20%, and 30%), their compressive strength increased by approximately 3.45 MPa in 1 day, 10.34 MPa in 7 days, and 6.89 MPa in 28 days. It should be noted that all concrete mixtures in **Figure 6(b)** had the same cement content as well as the same water-to-cement ratio. As a result, the increase in the compressive strength of concrete can be

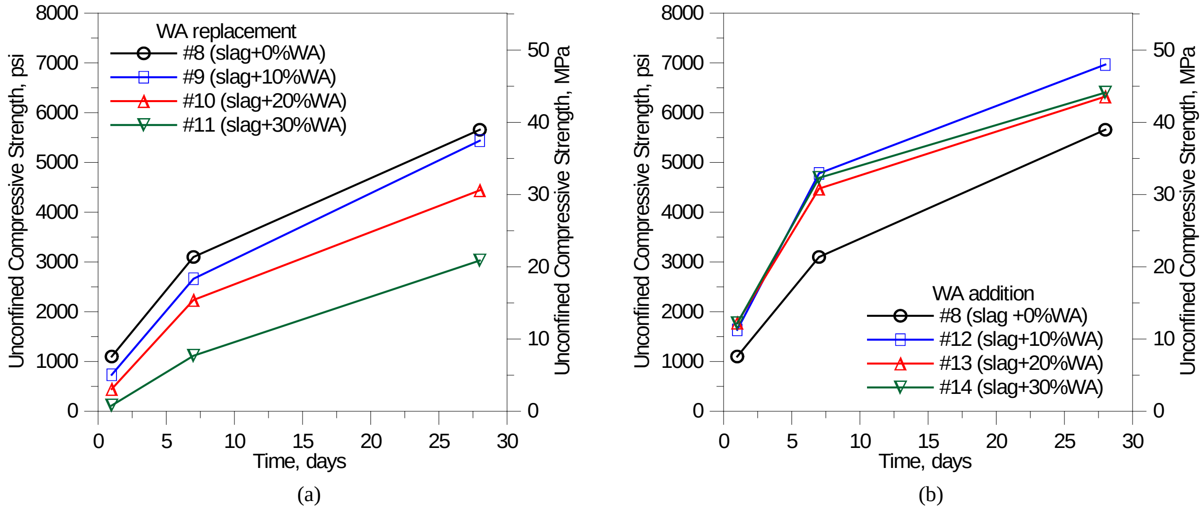


Figure 6. Effects of wood ash on compressive strength development of concrete blended with 40% slag.

reasonably attributed to the wood ash addition. This finding revealed that the wood ash helped to activate the slag-cement system. It has been a common concern in the concrete industry that the use of high volume slag to replace cement causes slows early strength gain. The result from this study revealed that adequately designing a slag concrete with the wood ash addition was able to substantially improve both the early-age and the 28-day compressive strength. It was interesting to note that for the three concrete mixtures with 10%, 20%, or 30% wood ash additions (**Figure 6(b)**), the early-age (1 to 7 days) compressive strength did not vary significantly; but a noticeable variation can be seen for the 28-day compressive strength. This can be again attributed to the unburned carbon particles remaining in the wood ash. These particles may not be critical to the concrete at its early age because the concrete was still weak, but they would become more and more important to the load carrying capacity of concrete as the concrete gained its strength over time. This was because the cracking can easily initiate on the sites occupied by the weak and brittle unburned carbon particles.

The effects of wood ash on the compressive strength development of concrete blended with10% silica fume are shown in **Figure 7**. The use of 10 to 30% wood ash to replace cement reduced the compressive strength of silica fume concrete (**Figure 7(a)**). This was again ascribed to the decrease in the cementitious material content. Interestingly, the 20% wood ash replacement caused the highest reduction in the compressive strength; while at the 30% wood ash replacement only a medium reduction was found.

Figure 7(b) gives the compressive strength development of concrete mixtures using wood ash as an addition. Depending on the wood ash content, different dosages of water-reducing admixtures were added for the purpose of achieving workable concrete with an approximately equal slump. In general, the wood ash addition did not significantly affect the compressive strength development of silica fume concrete. However, a small increase in the 1-day compressive strength was observed. This may be again due to the high alkaline content in wood ash that assisted in accelerating the hydration reaction of C_3S at the early age. Conversely, a small decrease in the 28-day compressive strength was seen and there were almost no changes on the 7-days compressive strength when the wood ash was introduced. This may be again caused by the dual effects of wood ash on the strength development of concrete. The high alkali helped to accelerate the early hydration reaction; while the unburned carbon would weaken the concrete. At 7 days, the positive effect of early acceleration was approximately offset by the negative impact of unburned carbon, leading to no significant variations on the compressive strength. At 28 days, the weakening effect of unburned carbon became dominant, causing the reduction in the compressive strength of concrete.

3.1.4. Free Dry Shrinkage

The free dry shrinkage measurement was performed on some selected mixtures and the results are summarized in **Table 3**. All concrete mixtures in **Table 3** exhibited a lower free dry shrinkage at both 7 and 28 days than the control mixture (#1), indicating that the wood ash replacement reduced the free dry shrinkage of concrete. This was because the wood ash was actually an aggregate filler and the use of wood ash to replace cement reduced

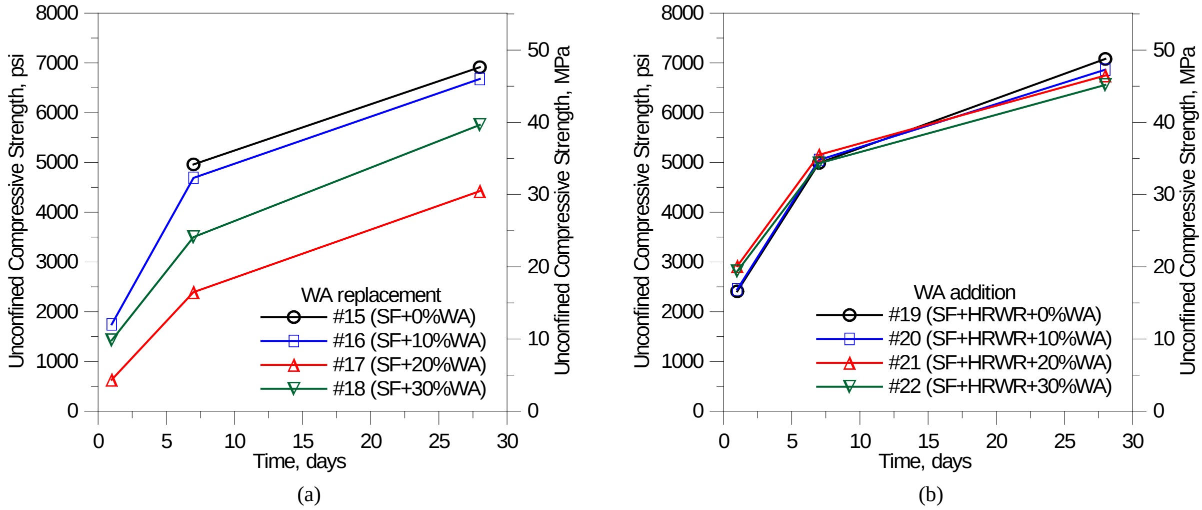


Figure 7. Effects of wood ash on compressive strength development of concrete blended with 10% silica fume.

Table 3. Results of free dry shrinkage measurements.

Mixture ID	Air dry (με)		Water curing (με)	
	7 days	28 days	7 days	28 days
#1 (Control)	−280	−520	+40	+50
#2 (10%WA replacement)	−185	−320	+5	+40
#3 (20%WA replacement)	−285	−395	+15	+45
#4 (30%WA replacement)	−210	−360	+10	0
#8 (slag + 0%WA)	−205	−485	+85	+120
#9 (slag + 10%WA replacement)	−195	−440	+315	+190
#10 (slag + 20%WA replacement)	−155	−245	+40	+170
#11(slag + 30%WA replacement)	−95	−215	+45	+15
#15 (SF + 0%WA)	−275	−480	+50	+90
#16 (SF + 10%WA replacement)	−195	−410	+20	+215
#17 (SF + 20%WA replacement)	−210	−355	+90	+225
#18 (SF + 30%WA replacement)	−255	−340	+140	+180

the paste content of concrete, thus reducing the dry shrinkage. However, there were no clear relationships between the percentage of wood ash replacement and the magnitude of free dry shrinkage, indicating that the wood ash had a complicated effect on the free dry shrinkage of concrete.

3.2. Effects of Wood ash on Properties of RCC

Seven RCC mixtures were tested in this study, in which the control mixture (#27) had a proportion that was typically used in the conventional RCC construction (cement = 296.5 kg/m^{3}and W/C = 0.36) [29]. The first series of tests (#28 to #30) used wood ash to partially replace cement; while in the second series (#31 to #33), the wood ash was incorporated as a partial replacement of sand. The workability (Vebe time), density, and compressive strength development of all these mixtures were measured and the results are listed in **Table 4**. It can be seen that the control mixture (no wood ash) exhibited the highest Vebe time, implying that the wood ash

Table 4. Effects of wood ash on main properties of RCC.

Mixture ID	Fresh properties		Compressive strength, MPa		
	Vebe time, s	Density, kg/m^3	1 day	7 days	28 days
#27 (Control)	35.9	2424	16.7	38.8	49.5
#28 (10%WA replacement)	17.8	2424	13.9	34.2	42.9
#29 (20%WA replacement)	26.7	2456	11.9	30.0	34.9
#30 (30%WA replacement)	22	2392	9.8	21.0	26.5
#31 (10%WA addition)	9.8	2361.6	16.7	34.0	43.3
#32 (20%WA addition)	17	2523.2	21.8	38.2	41.9
#33 (30%WA addition)	33.5	2302.4	23.0	36.7	39.8

replacement or addition helped to increase the consistency of RCC. In particular, low percentages of wood ash additions (#31 and #32) greatly reduced the Vebe time, indicating that 10-20% wood ash additions enabled the RCC mixtures to become easily compacted. This was again because the use of wood ash as an addition increased the amount of fines and improved the combined gradation of mixture, thus facilitating the compaction of RCC. In addition, more fines in the mixture increased the cohesiveness of mixture, thus reducing the risk of segregation. In addition, adding wood ash into RCC mixtures was found to affect the density of RCC. The 20% wood ash replacement or addition noticeably increased the density of RCC; while a noticeable drop in the density was noted for mixtures with 10% or 30% wood ash additions. Wood ash replacement or addition significantly influenced the compressive strength development of RCC. In general, the use of wood ash in RCC reduced its 28-day compressive strength, especially when the wood ash was used to replace the cement (#28 to #30). For examples, with an increase in the wood ash replacement from 10% to 30%, the 28-day compressive strength of RCC decreased by nearly 50%. However, different trends were observed for the early strength development. With an increase in wood ash replacement from 10% to 30%, the early age compressive strength (both 1 and 7 days) was reduced. For wood ash additions (#31 to #33), the 1-day compressive strength was increased by approximately 36%, but the 7-day compressive strength was slightly reduced. This result again reflected that the high alkali content of wood ash aided in accelerating the early hydration reaction of cement; whereas the high carbon content in wood ash would compromise the late-age compressive strength.

The result of this study indicated that the wood ash could be beneficially introduced into RCC as additional fines, which helped to improve the workability and the compactibility as well as enhance the early age strength development of RCC.

3.3. Effects of Wood Ash on Properties of Flowable Fill

In general, twelve flowable fill mixtures were developed in this study (as shown in **Table 5**), representing various levels of wood ash additions (40%, 50%, and 60% based on the mass of sand). Each proportion was developed based on a trial and error procedure. Initially, water and wood ash were added alternatively to the sand (27 kg, SSD). The flowability was measured every time after water or wood ash was added. A desirable mixture was selected as the one that displayed high flowability, low bleeding and low segregation. Then, different percentages of class F or C fly ash were added to these selected mixtures to partially replace wood ash for the purpose of further increasing flow and reducing bleeding and segregation. Finally, various cement contents were added to target the desired strength. The main properties of flowable fill mixtures developed in this study were measured and the results are summarized in **Table 6**. Basically, these mixtures can be classified into three types based on the 28-day compressive strength. The first type was a low strength flowable fill, which had a 28-day compressive strength of less than 0.69 MPa (#34). It used high volume wood ash to achieve desirable flowability and a small amount of cement (approximately 1.5% by the total weight of mixture) to attain the controlled low strength. The main disadvantage of this flowable fill was the excessive bleeding and subsidence. As a result, it could be potentially used for non-structural applications where easy future excavation with man power was favored.

Table 5. Materials and proportions of flowable fill with wood ash.

Mixture ID	Cement, kg	C Fly Ash, kg	F Fly Ash, kg	Wood Ash, kg	Sand, kg	Water, kg
#34	0.91	0	0	16.33	27.22	14.88
#35	0.91	0	2.72	13.61	27.22	11.79
#36	0.91	5.44	0	10.89	27.22	10.70
#37	0.91	0	5.44	10.89	27.22	10.39
#38	1.22	0	2.72	10.89	27.22	9.71
#39	1.22	0.91	0	10.89	27.22	10.43
#40	0	0	3.63	13.61	27.22	10.89
#41	0	0	6.35	10.89	27.22	9.23
#42	0	3.63	0	13.61	27.22	8.94
#43	0	6.35	0	10.89	27.22	8.86
#44	3.63	0	2.72	10.89	27.22	9.16
#45	3.63	2.72	0	10.89	27.22	10.08

Table 6. Basic properties of flowable fill with wood ash.

Mixture ID	Fresh Properties			Compressive Strength, MPa	
	Spread, mm	Bleeding, mL	Subsidence, mm	7 days	28 days
#34	254	270	19.05	0.2	0.46
#35	266.7	98.5	6.35	0.77	1.58
#36	254	22	Negligible	2.76	3.55
#37	285.8	56	Negligible	0.93	1.83
#38	266.7	189	3.18	0.82	1.69
#39	254	124	15.88	0.82	1.67
#40	317.5	96	6.35	0.73	1.42
#41	298.5	120	3.18	0.91	1.9
#42	254	128	3.18	0.84	1.85
#43	254	122	3.18	0.95	1.87
#44	279.4	100	3.18	1.65	3.47
#45	260.4	131	3.18	3.8	5.23

The second type was the medium strength flowable fill (#40 to #43) with a 28-day compressive strength of 1.38 MPa to 2.07MPa. It involved the use of class C or class F fly ash to partially replace the wood ash. The self-cementing class C fly ash, when hydrated with water, led to an increased compressive strength; while the pozzolanic class F fly ash when reacted with high alkaline wood ash would also result in strength gain. In addition, introducing class C or class F fly ash would assist in improving flowability and alleviating excessive bleeding and subsidence. This type of flowable fill would allow adequate in-place bearing capacity, while assuring easy removal of material with the power equipment. Another advantage of this flowable fill was the cost-saving due to the fact that no cement was needed in the mixture.

The third type was the high strength flowable fill, in which an increased cement content was used to achieve high 28-day compressive strength (more than 3.45 MPa). This was particularly obvious when the class C fly ash was present. For example, mixture #36 consisting of 20% class C fly ash and 40% wood ash supplemented with a small percentage (approximately 3.3%) of cement exhibited a compressive strength of over 3.45 MPa at 28 days. An increase in the percentage of cement to 13.3 (#45) substantially increased the 28-day compressive strength up to5.23 MPa. Similarly, a high percentage of cement (13.3%) together with 10% F fly ash and 40% wood ash (#44) also resulted in a high-strength flowable fill mixture with the 28-day compressive strength of more than 3.45 MPa. Obviously, these high strength flowable fills were more suitable for structural applications where the high bearing capacity was required.

It can be concluded that up to 60% wood ash can be successfully used in producing various types of flowable fill for different applications. The wood ash primarily acted as an aggregate filler in the mixture to assist the flow; while applying small effects on the strength gain. This was sometimes preferred as compared with the other supplementary cementitious materials such as class C fly ash because it was easier to control the strength development. In addition, the beneficial utilization of high-volume wood ash in flowable fill provided a way of alleviating the concern of wood ash disposal; while providing the concrete industry with a low cost material.

4. Summary and Conclusions

The wood ash can be successfully used in conventional slag concrete, roller compacted concrete, and flowable fill. In general, the use of wood ash to partially replace cement in conventional concrete was observed to have more impacts on the main properties of concrete as compared with the wood ash addition. The detailed findings were summarized as follows:

- Introducing wood ash into conventional concrete slightly influenced its workability, unit weight, and entrapped air content. The slump of concrete was normally reduced; but sometimes an increase in slump was noted, depending on the wood ash content and the type of supplementary cementitious materials used in the mixture. The unit weight was typically reduced with the wood ash replacement or addition. In addition, the wood ash increased the demand for the water-reducing and air-entraining admixtures.
- The use of wood ash in conventional concrete generally decelerated the setting of concrete. However, in some cases, the wood ash addition (*i.e.* as a partial replacement of sand) was seen to accelerate the setting of concrete particularly when the concrete contained the blast furnace slag.
- Using the wood ash to partially replace cement in conventional concrete reduced its early-age and 28-day-compressive strength; while the use of wood ash as an addition did not significantly affect the compressive strength development of concrete. In most cases, the wood ash addition helped to increase the early-age compressive strength of concrete. However, the 28-day compressive strength was slightly reduced. Specifically, a remarkable increase in both the early age and the 28-day compressive strength was observed when the wood ash was added to the concrete that consisted of 40% slag. In addition, the wood ash reduced the free dry shrinkage of concrete.
- Similarly, the wood ash addition or replacement was found to affect the properties of RCC. In general, the use of wood ash in RCC helped to facilitate the compaction and reduce the risk of segregation. It also reduced the 28-day compressive strength especially when the wood ash was used as a partial replacement of cement. However, the wood ash addition was observed to improve the early-age compressive strength. These results indicated that wood ash could be positively incorporated into RCC mixtures to enhance the workability without significantly sacrificing the strength.
- Up to 60% of wood ash by weight of sand was successfully incorporated into the flowable fill mixtures in this study. When combined with Portland cement, class C or class F fly ash, the wood ash could be used to design various types of flowable fill for different applications.

Acknowledgements

The authors acknowledge the financial support from the Department of Energy with UT-Battelle, LLC, management and operations contractor of the Oak Ridge National Laboratory pursuant to DOE Contract Number DE-AC05-00OR22725. A part of this work was performed through the Senior Concrete Laboratory class at the Middle Tennessee State University; as such the authors acknowledge the assistance from the students for the specimen preparation and testing.

References

[1] Fehrs, J.E. (1996) Ash from the Combustion of Treated Wood: Characterization and Management Options. The National Bioash Utilization Conference, Portland, 20 p.

[2] Naik, T.R. (2000) Flowable Slurry Incorporating Wood Fly Ash from the Weyerhaeuser Company. Report No. CBU-2000-01, Rep-367, UWM Center for By-Products Utilization, University of Wisconsin-Milwaukee, 37 p.

[3] Naik, T.R., Siddique, R. and Kraus, R.N. (2003) Properties of Flowable Slurry Containing Wood Ash. 6*th CANMET/ACI International Conference on Durability of Concrete*, Thessaloniki, June 2003, 13 p.

[4] Naik, T.R., Kraus, R.N. and Siddique, R. (2003) Controlled Low Strength Materials Containing Mixtures of Coal Ash and New Pozzolanic Material. *ACI Material Journal*, **100**, 208-215.

[5] Naik, T.R. and Kraus, R.N. (2003) A New Source of Pozzolanic Material. *ACI Concrete International*, 55-62.

[6] Ban, C.C. and 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. http://dx.doi.org/10.1016/j.resconrec.2011.02.002

[7] Udoeyo, F.F., Inyang, H., Young, D.T. and Oparadu, E.E. (2006) Potential of Wood Waste Ash as an Additive in Concrete. *ASCE Journal of Materials in Civil Engineering*, 605-611. http://dx.doi.org/10.1061/(ASCE)0899-1561(2006)18:4(605)

[8] Rajamma, R., Ball, R.J., Tarelho, L.A.C., Allen, G.C., Labrincha, J.A. and Ferreira, V.M. (2009) Characterization and Use of Biomass Fly Ash in Cement-Based Materials. *Journal of Hazardous Materials*, **172**, 1049-1060. http://dx.doi.org/10.1016/j.jhazmat.2009.07.109

[9] Wang, S., Miller, A., Llamazos, E., Fonseca, F. and Baxter, L. (2008) Biomass Fly Ash in Concrete: Mixture Proportioning and Mechanical Properties. *Fuel*, **87**, 365-371. http://dx.doi.org/10.1016/j.fuel.2007.05.026

[10] Wang, S. and Baxter, L. (2007) Comprehensive Study of Biomass Fly Ash in Concrete: Strength, Microscopy, Kinetics and Durability. *Fuel Processing Technology*, **88**, 1165-1170. http://dx.doi.org/10.1016/j.fuproc.2007.06.016

[11] Wang, S., Miller, A., Llamazos, E., Baxter, L. and Fonseca, F. (2008) Durability of Biomass Fly Ash Concrete: Freezing and Thawing and Rapid Chloride Permeability Tests. *Fuel*, **87**, 359-364. http://dx.doi.org/10.1016/j.fuel.2007.05.027

[12] Etiegni, L. and Campbell, A.G. (1991) Physical and Chemical Characteristics of Wood Ash. *Bioresource Technology*, **37**, 173-178. http://dx.doi.org/10.1016/0960-8524(91)90207-Z

[13] Meyers, N.L. and Kopecky, M.J. (1998) Industrial Wood Ash as a Soil Amendment for Crop Production. *TAPPI Journal*, **81**, 123-130.

[14] ASTM C136-06. Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates.

[15] ASTM C188-95. Standard Test Method for Density of Hydraulic Cement.

[16] ASTM C114-00. Standard Test Methods for Chemical Analysis of Hydraulic Cement.

[17] ASTM C192-02. Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory.

[18] ASTM C143/C 143M-08. Standard Test Method for Slump of Hydraulic-Cement Concrete.

[19] ASTM C138/C 138M-09. Standard Test Method for Air Content of Freshly Mixed Concrete by the Pressure Method.

[20] ASTM C231-04. Standard Test Method for Air Content of Freshly Mixed Concrete by the Pressure Method.

[21] ASTM C403/C403M-06. Standard Test Method for Time of Setting of Concrete Mixtures by Penetration Resistance.

[22] ASTM C157/C157M-06. Standard Test Method for Length Change of Hardened Hydraulic-Cement Mortar and Concrete.

[23] ASTM C39/C39M-05. Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens.

[24] ASTM C1170-06. Standard Test Method for Determining Consistency and Density of Roller-Compacted Concrete Using a Vibrating Table.

[25] ASTM C1176-05. Standard Practice for Making Roller-Compacted Concrete in Cylinder Molds Using a Vibrating Table.

[26] ASTM D6103-97. Standard Test Method for Flow Consistency of Controlled Low Strength Material (CLSM).

[27] Mehta, P.K., Monteiro, P.J.M. (1993) Concrete: Microstructure, Properties, and Materials. 2nd Edition, The McGraw-Hill Companies, Inc., 548 p.

[28] Roberts, L.R. and Taylor, P.C. (2007) Understanding Cement-SCM-Admixture Interaction Issues. *ACI Concrete International*, **29**, 33-41.

[29] ACI 327R-14 (2015) Guide to Roller-Compacted Concrete Pavements. Technical Documents, 51 p.