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EFFECT OF PARTIAL REPLACEMENT OF SAND BY MSWI-BA ON THE PROPERTIES OF MORTAR

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Abstract

Disposal of municipal solid wastes (MSW) has recently become a major problem in Lebanon as finding appropriate landfill is becoming more challenging than ever. Incineration is a technique currently used to reduce the volume of MSW generated. The output of this treatment is a residue well known as Municipal Solid Waste Incineration bottom and fly ash. This study is focused on the mortar containing Municipal Solid Waste Incineration Bottom Ash (MSWI-BA) as partial replacement of sand. For this purpose, mortar specimens were prepared with 25, 50 and 100% (by weight) MSWI-BA to replace the sand. Specimens were cured in water for 2, 7, 14, 28 and 56 days. Testing included; compressive strength, ultrasonic pulse velocity (UPV), density, capillary water absorption (CWA) and total water absorption (TWA). Results indicate that 25% of sand can be replaced with MSWI-BA without significant alterations in mortar properties. Above 25% replacement levels, there is drastic decrease in compressive strength and UPV. The absorption by total immersion and capillary rise was found to increase as the replacement levels of sand by MSWIBA go up from 25% to 100% but significantly diminish as the curing duration increases beyond 7 days.

Keywords

Capillary water absorption, mortar, municipal solid waste incineration bottom ash (MSWI-BA), sand, strength, UPV, waste

1. INTRODUCTION

In the modern world, sustainability is an ultimate objective that every country is striving for. Central to this point is the recycling and reuse of waste products in construction activities. These wastes can be residues from various industries including coal power stations and steel industry. These waste can be used in concrete and mortar to partially substitute the sand or cement (Ghanem et al. 2019, Machaka et al. 2019, Baalbaki et al. 2019, Abdulmatin et al. 2018, Lynn et al, 2017, Dou et al. 2017, Wongsa et al. 2017, Saikia et al. 2015, Jiang et al, 2009). One of the major problems facing Lebanon nowadays is the generation and disposal of waste. Latest study in 2016 indicates that 2.04 million tons of municipal solid waste (MSW) are produced annually (Massoud et al. 2016). The MSW is composed of 52.5% organic waste, 16% paper, 11.5% plastic, 5.5 metal and 3.5% glass. It is expected that the amount of MSW generated has increased dramatically since that time as the number of Syrian refuges has increased over the last few years. In Lebanon, dumping and landfilling are considered the main ways of disposing the MSW. However, these wastes are harmful to the Lebanese society as a whole and to the environment due to the presence of heavy metals and the emission of dangerous gases such as methane. During the last decade, several technologies have been developed to deal with this problem. One of the attractive options is the thermal treatment technology also known as the incineration technique as it reduces the MSW by 70% by mass and 90% by volume (Lynn et al 2017). The incineration technique consists of feeding the furnace by MSW at temperature above 800ºC to ensure complete burning. Heat generated is used by a boiler to generate electricity. Once the MSW has been burned out, a residue is ejected from the bottom of the combustion chamber called bottom ash (BA) and represents around 25% by weight of MSW (Becquart et al 2009). The BA are large particles that have similar appearance to silty sand and gravel and are considered non-toxic (Siddique 2010). Another residue from the incineration technique is collected from the exhaust gas cleaning systems and known as Municipal Solid Waste Incineration fly ash (Charbaji et al. 2018a, Charbaji et al. 2018b, Bertolini et al. 2004). These ashes are considered hazardous and contains significant amount of heavy metals (e.g. Zn, Pb, Cu, Cr, Cd and Ni) and dangerous substances in addition to organic compounds (An et al 2017; Yang et al 2018).

Construction industry depletes large amount of virgin quarried materials (coarse and fine aggregate). An interesting alternative for the industry is to use these by-products and wastes in construction applications. Previous studies have used the MSWI-BA as partial replacement of cement in mortar products but their conclusions were not conclusive (Jaturapitakkul et al. 2003; Pan et al. 2008). Other researchers have focused on using the MSWI-BA as partial replacement of fine aggregate in concrete and determined that although BA is considered non-hazardous, there is still uncertainty regarding its engineering behavior which forestall its use in construction (Saad et al. 2019, Berg and Neal 1998). The objective of this study is to investigate the effect of MSWI-BA as a partial replacement of sand on mortar properties. If results derived from this study deems promising, the BA will then be considered a renewable resource in the construction industry, eventually decreasing the amount of aggregate excavated from the quarries.

2. EXPERIMENTAL STUDY

2.1 Materials

In this work, the cement used is ordinary Portland cement type I received from Siblin plant located in Mount Lebanon and complies with all Lebanese standards (LIBNOR NL 53, 1999). It has a fineness of 4174 cm^2/g. Sand used in the mixes was obtained from Dibbieh area and has a fineness modulus of 2.7. Sieve analysis conducted on the sand indicates that it meets the requirement of ASTM C33 (Fig 1a). Portable water was used in all mortar mixes. As workable mixes were targeted, superplasticizer [Sikament] was added at the dosage recommended by the manufacturer. MSWI-BA was collected from SICOMO plant located in Bar-Eliace, Lebanon. The ashes were sieved to determine their gradation as illustrated in Fig 1b. The maximum particle size of BA was less than 12.5 mm.

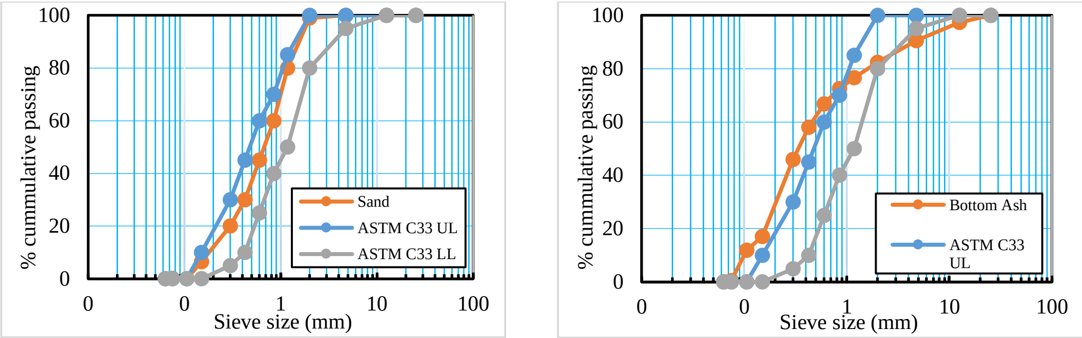


Fig.1: particle size distribution a) sand, b) bottom ash

The chemical composition of BA was determined using X-Ray Fluorescence (XRF) analysis. The XRF test was conducted at Sibline cement factory laboratory in Lebanon. BA sample preparation started by drying the sample at 105˚C till obtaining constant mass. A portion of the dried sample was taken to test the loss on ignition (LOI) which was determined by igniting the sample at 950˚C until constant mass. The obtained results are shown in Table 1. As shown, the presence of Si2O3 (21.1%), Al2O3 (13%), Fe2O3 (8%) and significant amount of CaO (35.9%) can reveal good hydraulic properties, although the summation of oxides was found to be 42% which is less than 70% as mentioned in ASTM C618. The sulfur content SO3 was 0.28% which is in the normal range (< 4%) whereas the obtained Loss of Ignition (15.5%) is greater than 4%. The high alkalinity solution caused by the high CaO content, can stabilize the heavy metals. These include Cadmium, Copper and Lead. Therefore, based on the above, the BA don't meet all the requirements stipulated in ASTM C618 to be considered a pozzolanic materials.

Table 1: Chemical composition of cement and bottom ash (% mass)

Components	**SiO_2**	**Al_2O_3**	**Fe_2O_3**	**CaO**	**MgO**	**SO_3**	**K_2O**	**Na_2O**	**Cl**	**LOI**
Cement	18.3	3.95	3.08	61.33	1.77	3.06	0.47	0.13	0.046	6.73
MSWI-BA	21.1	13.08	8.07	35.93	1.37	0.28	0.14	0.5	1.7	15.55

2.2 Mix Design

Four mortar mixes were investigated in this study. The sand was replaced with 0%, 25%, 50% and 100% MSWI-BA. The absolute volume method was adopted in designing the mixes. The water cement ratio for all mixes was fixed at 0.4 and the ratio of cement to sand was equal to 3. Air entrainer is added to obtain a 2% air in the mixes. The total number of specimens tested is 200. The key mix design information is presented in Table 2.

Table 2: Details of mortar mixes

Mix #	**MSWI-BA Content (%)**	**W/C ratio**	**Water (kg/m^3)**	**Cement (Kg/m^3)**	**MSWI-BA (Kg/m^3)**	**Sand (Kg/m^3)**
1	0	0.4	161	402.8	0	1209.6
2	25	0.4	161	402.8	302.4	907.2
3	50	0.4	161	402.8	604.8	604.8
4	100	0.4	161	402.8	1209.6	0

2.3 Specimen Preparation and Testing

Mortar specimens were prepared in the construction materials laboratory at Beirut Arab University in the following sequence in accordance with ASTM C305. First, the mixing water was added to the paddle and bowl mixer. Second, the cement was added to the mixer and the mixer was switched on for 30 seconds at slow speed (140 ± 5 rpm). Then the sand and the MSWI-BA were mixed together and added gradually to the bowl mixer while still mixing at slow speed. The mixer is then switched off and the speed of the mixer is raised to 285 ± 10 rpm. This was followed by another 30 seconds mixing followed by 90 seconds resting period. This will allow for any materials that have been collected on the sides of the bowl to be scraped down. Finally, the mixer was switched on for a final 60 seconds at medium speed. To check mortar workability, the flow test was conducted according to ASTM C1437. From caliper measurements, it was found that the flow of mortar for all mixes fall in the 95-105% range indicating acceptable workability. Immediately after the flow test is complete, the mortar was directly poured into the molds. For the compressive strength, ultrasonic pulse velocity (UPV), density, total water absorption (TWA) and capillary water absorption (CWA) tests, standard cubes specimens with internal dimensions 50×50×50 mm were used.

It is well known that mortar compressive strength is closely correlated to its quality. In this study, compressive test was conducted according to ASTM C109 on 2 inches mortar cubes at a rate of 1.4 kN/sec until failure.

The UPV test is a non-destructive popular test that is based on measuring the time needed for an ultrasonic wave to pass through a known path length of concrete. It is considered a measure of concrete quality. Table 3 provides the classification of concrete quality based on UPV values. As shown in the table, higher values mean higher concrete quality in terms of density and uniformity. On the other side, lower UPV values indicates concrete non-uniformity and cracks or voids presence.

Table 3: Classification of the quality of concrete on the basis of pulse velocity (IAEA 2002)

Pulse Velocity	Quality of Concrete
>4.5 km/s	Excellent
3.5 – 4.5 km/s	Good
3.0 – 3.5 km/s	Doubtful
2.0 – 3.0 km/s	Poor
<2.0	Very poor

The TWA test was conducted to determine the percentage of water absorbed into the interconnectivity pores in the mortar matrix. It is a considered a relevant parameter from the point of view of durability performance indicators. Many factors like water cement ratio, mix proportions, curing duration, presence of mineral and chemical admixtures directly affect the TWA values. Mortar samples were tested at 2, 7, 28 and 90 days. Before testing, specimens are placed in an oven at 80oC for 48 hrs until a constant weight is reached. The cubes are then immersed in water for 24 hrs and the TWA is expressed as an increase in weight as a percentage of the original weight.

CWA is the movement of water particles through the mortar matrix without an external applied gradient. Among primary transport mechanisms, CWA is considered the most faster and damaging. In this study, CWA was conducted as per ASTM C1585. Following pre-conditioned at 80oC, the cubes specimens are partially immersed in water (up to five mm from the bottom of the cubes). To avoid evaporation and maintain uniaxial water flow, the four sides of the cubes were sealed with a non-absorbent coating. The bottom and top sides were left unsealed and the sample weight was recorded at predetermined intervals (20, 30, 60, 120, 140 min and 1, 2 and 3 days) was measured to an accuracy of 0.1g.

3. RESULTS AND DISCUSSION

The results of the compressive strength, UPV, density, TWA and CWA tests, data analysis and the correlation between the four tests will be presented in the following sections. Also a short description of each test procedure will be provided.

3.1 Compressive Strength

The development of compressive strength with age for all mixes are presented in Fig 2. Several points can be made. First, the importance of the age of curing on strength is well illustrated in the Figure. The strength increases with the age of curing irrespective of the amount of MSWI-BA in the mix. For example, for mix 3 containing 50% MSWI-BA as a partial replacement of sand, the compressive strength of mortar cubes are 4.3, 7.1, 10.2, 12.5 and 14.1 MPa at 2, 7, 14, 28 and 56 days curing. Those results are very much anticipated as mortar microstructure becomes denser with an increase in curing durations as more hydration products (calcium silicate hydrate and calcium hydroxide) are formed with time. This will eventually lead to a reduction in the capillary pore and consequently denser structure. Second, the effect of MSWI-BA on mortar compressive strength is important to observe. At 25% replacement level of sand, the compressive strength of mortar is less than the control sample up to 7 curing days, but topped the control strength at higher curing durations. For example, the mortar strength at 25% sand replacement is 16.5 MPa whereas the control one is 24.3 MPa. At higher curing durations, the strength raises to 36.1, 43.5 and 45.1 MPa while the control one reaches 32.1, 40, and 42.3 MPa respectively at 14, 28 and 56 curing days. These previous results indicate that some sort of pozzolanic reaction took place at this replacement level (25%). On the other side, as the % of MSWI-BA replacement level increases from 25% to 50% and 100%, the relationship between the mortar strength and the amount of MSWI-BA becomes inversely proportional. In other words, a steep decline in strength can be noticed at the 50% and 100% replacement level. For example, the compressive strength at 25% MSWI-BA is 4.9, 16.5, 36.1, 43.5 and 45.1 MPa whereas it is 4.3, 7.1, 10.2, 12.5, and 14.1 MPa for mix containing 50% MSWI-BA. This is likely attributed to the following mechanism: MSWI-BA is a porous material with an absorption capacity in the range of 10%. It is possible that the MSWI-BA at those high replacement levels (50% and 100%) had absorbed the water in the mix reserved for hydration, therefore hindering the hydration system and the cementitous reaction. It should be noted here that BA is considered a weaker material than sand. The specific gravity of sand is 2.65 whereas it is 2.3 for MSIW-BA. Therefore, substituting stronger material with a weaker material will ultimately lead to a decline in the mechanical strength.

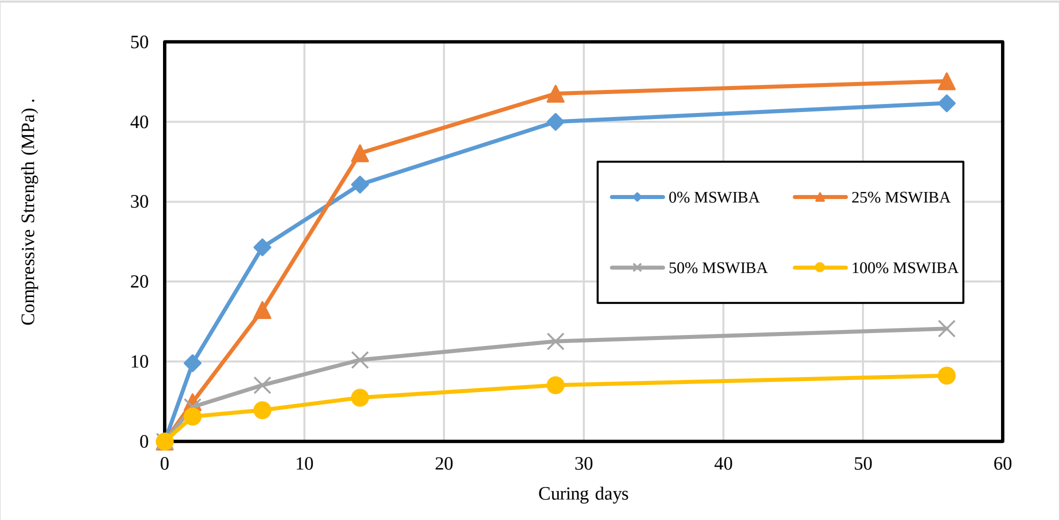


Fig.2: Effect of curing duration on mortar compressive strength

As it is in the interest of concrete/mortar technologists to determine the maximum amount of MSWI-BA that can be incorporated in the mix, the % increase/decrease in compressive strength was determined at all curing durations. Results are presented in Fig 3. As seen in the bar charts, the % drop in mortar strength is very significant for mix containing high percentage of MSWI-BA. For example, at 56 days of curing, this drop reaches 67% and 81% for mix having 50% and 100% sand replacement by MSWI-BA. On the other side, mortar strength increases 12%, 9% and 6% at 14, 28 and 56 days curing when the amount of MSWI-BA is at 25% replacement level. This can be attributed to two phenomena: pozzolanic reaction mentioned previously and to the fact that the MSWI-BA used in this study contains some amount of fines, leading to a better gradation of the particles in the mortar matrix and therefore achieving higher compactibility.

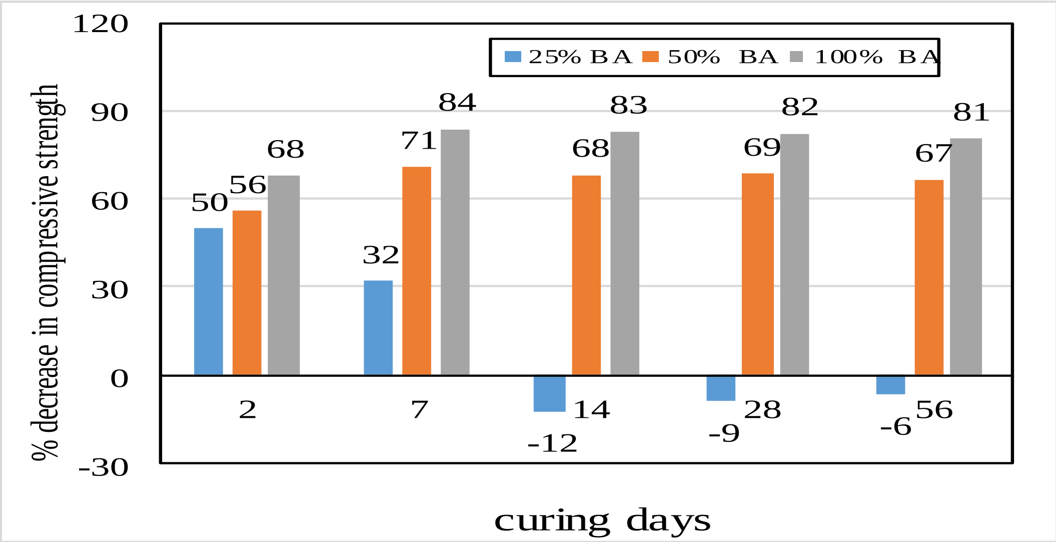


Fig.3: % decrease in compressive strength

To determine accurately the amount of MSWI-BA allowed in the mix, the pozzolanic activity index (PAI) needs to be assessed. According to ASTM C311 and C618, samples with PAI greater than 75% at 28 days are considered to have a positive PAI. The PAI values for all mixes at all curing durations are presented in Fig 4. It is evident from the plot that mixes having 50% and 100% of sand replaced by MSWI-BA yields very low PAI values. For example, the PAI values are 44%, 29% 32%, 31% and 33% at 2, 7, 14, 28 and 56 days respectively, much lower than the minimum threshold of 75%. On the other side, mix 2 having 25% sand replaced by MSWI-BA yields 112%, 109% and 106% PAI values at 14, 28 and 56 days. Consequently, it can be deducted based on the PAI results that the MSWI-BA can be used in mortar if the sand replacement levels does not exceed 25%.

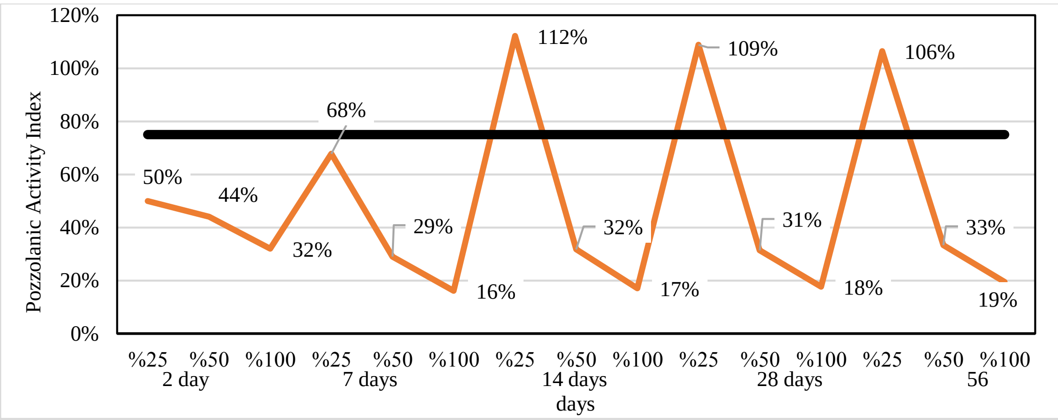


Fig.4: Pozzolanic activity index for all mixes

3.2 Density

The density of MSWI-BA is lower than that of natural sand. Thus, when using MSWI-BA as partial replacement of sand in mortar, the density is expected to decrease as percentages of MSWI-BA goes up in the mixes. Fig 5 shows the densities for all mixes at all curing durations. The weight used to calculate the density is the dry weight where the cubes are removed from water and put in an oven for 48 hrs until constant mass is reached. As shown in Fig 5, when 25% of sand is replaced by MSWI-BA, the densities topped slightly the density of the control sample after two weeks of curing. For example, the densities for mix 2 are 2202 kg/m^3, 2208 kg/m^3 and 2218 kg/m^3 at 14, 28 and 56 days of curing whereas it is 2144 kg/m^3, 2161 kg/m^3 and 2177 kg/m^3 for the control mix. This can be attributed to the fact that the density of mortar is not only dependent on the mix ingredients densities but also on the calcium silicate hydrate gels produced during the cementitious reaction. At early ages (first two weeks), MSWI-BA reacts slowly with calcium hydroxide liberated during cement hydration and does not contribute significantly to the densification of concrete matrix. In the later stages, pozzolanic reaction starts to take place leading to denser matrix and therefore higher density. In this case (25% MSWI-BA), this raise is not significant. On the other side, it can be noticed a drop in the densities for mix containing 50% and 100% of sand substituted by MSWI-BA. For example, the density for the control sample is 2161 kg/m^3 at 28 days curing whereas it is 1698 kg/m^3 for mix 4 containing 100% MSWI-BA. This corresponds to a 21% decrease. A similar decrease in density is noticed at all curing duration for mix 3 and 4. This can be attributed to the fact that water requirement increases with an increase in the level of sand replaced by BA. A relatively higher water-solids ratio produces weaker and pervious matrix, ultimately leading to a lower density.

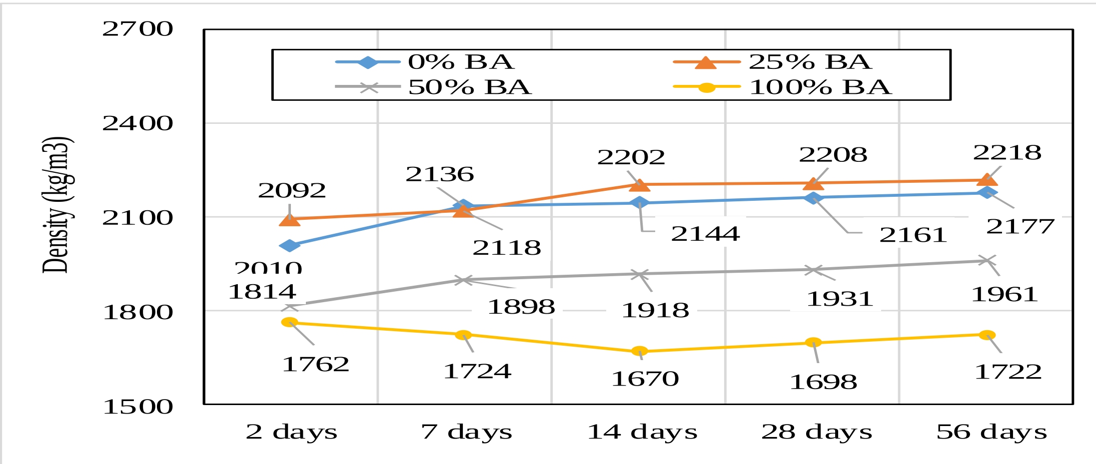


Fig.5: Effect of MSWIBA on mortar density

3.3 Ultrasonic Pulse Velocity

The effect of fine aggregate replacement by MSWI-BA on mortar is shown in Fig 6. Many points can be deduced from the obtained results. First, all UPV values of Mix 3 and Mix 4 (50% and 100% sand replacement by MSWI-BA) at all curing durations fall in the 2-3 range indicating poor mortar quality. One possible explanation is that MSWI-BA with its high absorption capacity leads to the creation of voids resulting in lower UPV values. Thus it can be concluded that the use of MSWI-BA at the high sand replacement percentage (50% and 100%) affects negatively the quality of mortar. Second, the relation between the amount of MSWI-BA and UPV in the mixes appears to be inversely proportional. For example, the UPV values for mix 2 (25% MSWI-BA) are 3.69, 3.88 and 4.1 km/sec whereas it is 2.91, 2.94 and 3.03 km/sec for mix 3 (50% MSWI-BA) at 14, 28 and 56 curing days. UPV values then decrease further for mix 4 (100% MSW-BA) to reach 2.43, 2.53 and 2.73 km/sec 14, 28 and 56 curing days.

This may be attributed to the compatibility of the mixes that was negatively affected by the presence of BA at high dosage levels.

Third, it can be seen that UPV values for mix 2 (25% of sand replaced by MSWI-BA) are above 3.5 km/sec classifying effectively the mortar as good. This may be attributed to two points: better compactibility of the mix at the 25% sand replacement level by MSWI-BA and mortar microstructure becomes denser due to filling of pores with extra CSH gel formed by the pozzolanic action of MSWI-BA. Fourth, within the same mix, UPV values increase proportionally with an increase in curing duration and this is very much anticipated as hydration products are continuously formed with the availability of moisture in the mix contributing to the uniformity and strength of mortar.

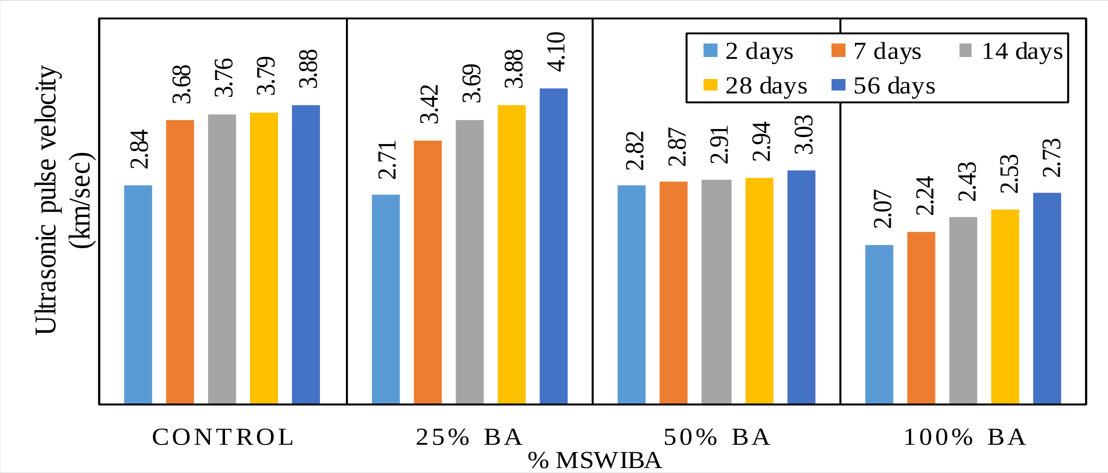


Fig.6 : Effect of MSWI-BA on UPV

3.4 Total Water Absorption (TWA)

TWA results are presented in Fig 7. It can be seen that the relationship between the amount of MSWI-BA in the mix and the TWA is proportional. For example, at 28 days, the TWA is 5.2%, 6.9%, 16.7% and 17.8% for specimens containing 0%, 25%, 50% and 100% MSWI-BA respectively. This corresponds to an increase of 32%, 221% and 242% increase in TWA values with reference to the control sample. This can be attributed to the amount of fines in the MSWI-BA, and as the amount of fine increases in the mix, the total surface area goes up as well leading to higher water absorption. Regarding curing duration, TWA results indicate that it is not the main factor affecting mortar absorption capacity in the first week following casting. However, it plays a significantly role in reducing TWA after a period of four weeks, and this deduction can be noticed for all mixes. For example, for mix 2 (25% of sand replaced by MSWI-BA), the TWA increases from 8.2% to 11.8% when curing duration increases from 2 to 7 days and this is considered very perplexing considering that an increase in curing should decrease water absorption. This is then followed by a sharp decline to 6.9% and 4.5% at 28 and 56 days respectively. This unexpected behavior is likely attributed to the following: initially (during the first week of curing), particle size distribution of MSWI-BA plays a major role in determining mortar porosity. In the later stages, hydration products (in part because of the pozzolanic reaction) distribution and compactibility of the mix become the dominant factor. From the plot, it can be noted that mix 1 (control) and mix 2 (25% MSWI-BA) yield the lowest TWA values (4.5%) at 56 days. Therefore, it can be concluded that the presence of 25% MSWI-BA as a partial replacement of sand is beneficial in reducing TWA.

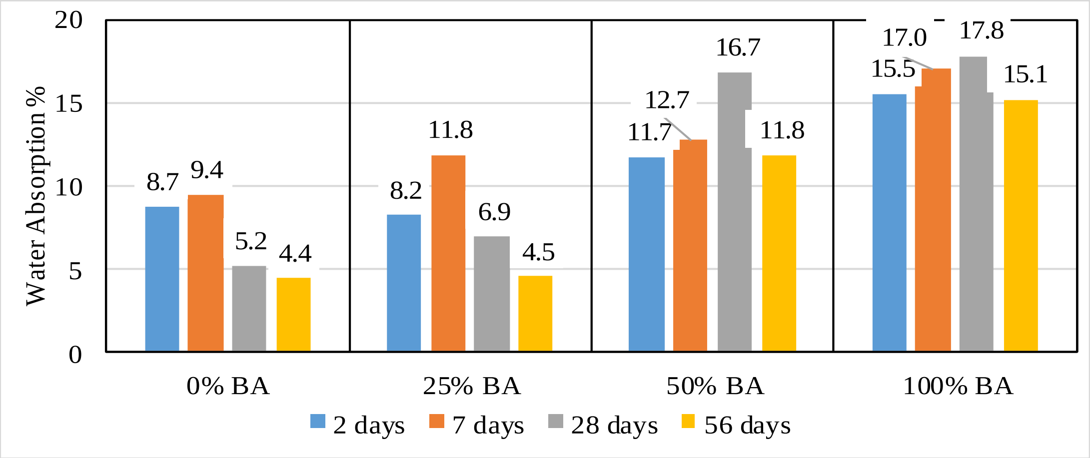
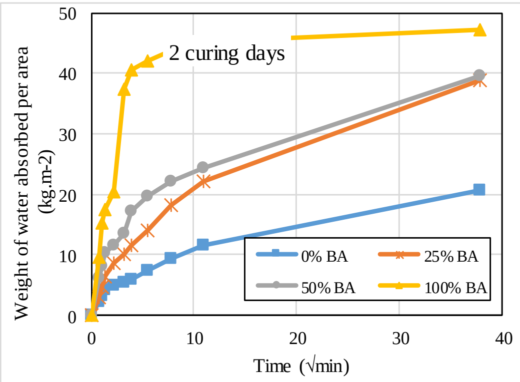


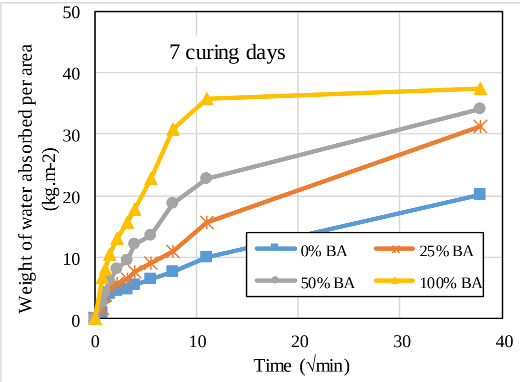
Fig.7: Effect of MSWI-BA on TWA

3.5 Capillary Water Absorption (CWA)

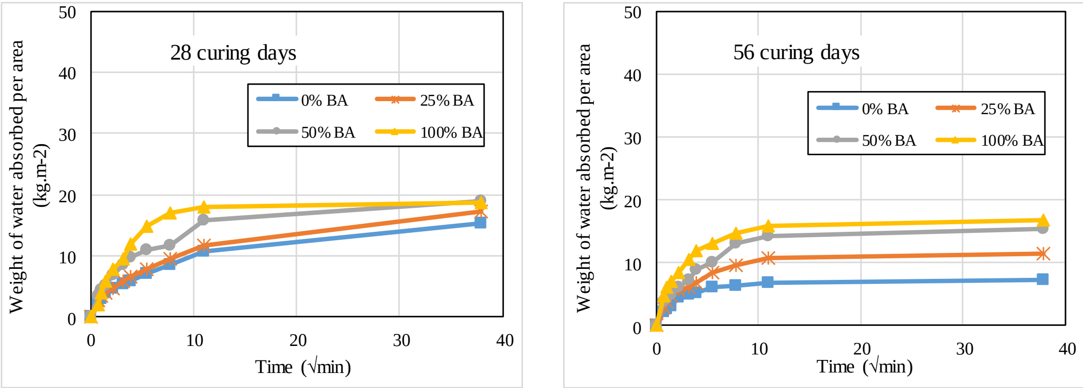
CWA results are presented in Fig 8. As shown, all plots show similar characteristic patterns. A rapid increase in percentage of water absorbed per surface area is noticed up to two hours. This is then followed by a mild increase and then the results somewhat stabilized afterwards. For example, for mix 3 containing 25% MSWI-BA at 56 days of curing, the % of water absorbed is 3.9%, 8.4% 10.8% and 11.4% at 1 min, 10 min, 30 min and 1440 min respectively. This corresponds to a 59%, 29% and 5.5% increase respectively. This increase in weight with time is due to the following set of reactions. At the beginning of the test, the percentage of water in the pores on the surface of the cubes is at its minimum as the cubes were before that placed in the oven. Thus, the high amount of water absorbed is at its highest. As the pore surfaces becomes partially saturated within the first day, the amount of diffused water thought capillary action goes down. It can be seen as well from the plots that the amount of water absorbed increases as the percentage of sand replaced by MSWI-BA goes up. This may be due to the high absorption of MSWI-BA yielding to a high porosity mortar which lead to higher capillary absorption. At later age (28 days and beyond), the volume of pores in mortar decreases due to the continuity of the hydration process.



(a)



(b)



(c) (d)

Fig.8: The effect of MSWI-BA on the capillary water absorption with time (sqrt) at different curing durations. (a) 2 days (b) 7 days, (c) 28 days and (d) 56 days

CWA test was conducted to determine the sorptivity coefficient (well known as the CWA coefficient) of mortar cubes. From weight measurement previously calculated, the sorptivity coefficient (S) can be calculated by the following expression: $S = (Q/A)/\sqrt{t}$

Where: Q is the volume of water absorbed (cm3), A is the surface area in contact with water (cm2) and t is the time (s). S was obtained from the slope of the linear relationship between Q/A and $\sqrt{t}$. Results for all mixes are presented in Fig 9a. Several points can be deducted. First, the relation between MSWI-BA and sorptivity appear to be proportional, regardless of the amount of curing. In other words, the sorptivity goes up as the % of MSWI-BA increases in the mix. For example, at 56 curing days, the sorptivity values are 0.62, 0.60, 1.07 and 2.17 for mixes containing 0%, 25%, 50% and 100% of sand replaced by MSWI-BA. This can be explained as follows: within the first two weeks following casting, the water needed for hydration originates from the water added during mixing. With time, the hydration rate decreases gradually. As MSWI-BA is hygroscopic in nature, it has a tendency to absorb water located in the capillary pores of the mortar matrix. This will directly raise the capillary forces in the matrix. Therefore, any increase of MSWI-BA in the mix will eventually lead to a surge in sorptivity values. Second the importance of curing is well illustrated in the results. A decrease in sorptivity values is accompanied by an increase in curing duration (2.87 at 2 days versus 0.83 at 28 days). This can be attributed to the fact that curing improves the hydration process leading to a dense microstructure that lead to a decrease in mortar permeability. Consequently, it will become more difficult for water to penetrate deeper into the mortar matrix through capillary forces that are significant in the superficial layers that present open and connected pores.

Current literature (Machaka et al. 2019) indicates that lower sorptivity values are attributed to better mortar performance, specifically its durability. In spite of the fact that achieving 0% absorption is not realistic, it is in the interest of the researchers to calculate the % increase/decrease of CWA coefficient as this will help determine the optimum amount of MSWI-BA used in the mix without compromising its durability. Results presented in Fig 9b indicate that adding 25%, 50% and 100% MSWIBA as a replacement of sand increase the CWA coefficient by 26.9%, 148.4% and 154.4% respectively at 7 days curing. On the other side at 56 days of curing, the CWA coefficient decrease 1.9% at 25% MSWI-BA replacement level but increase to 73.6% and 253.2% at 50% and 100% replacement level of MSWI-BA respectively. Based on the CWA analysis, it can be concluded that replacing natural sand by MSWI-BA at the 25% replacement level affect positively mortar absorption properties.

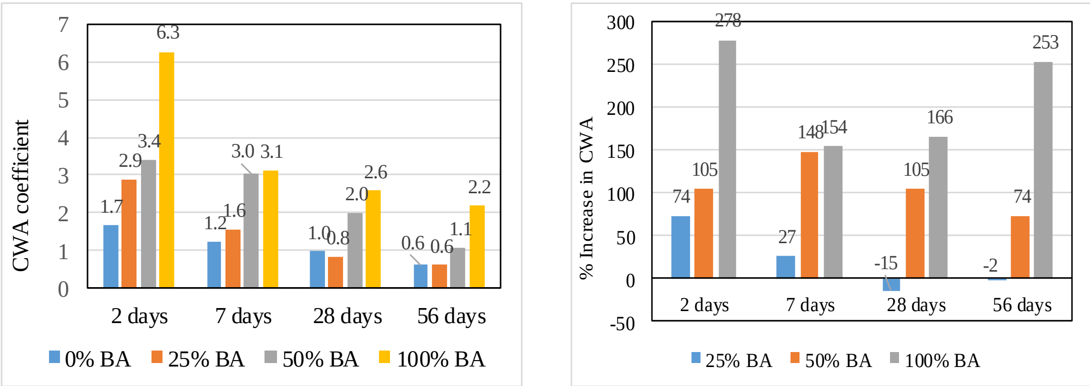
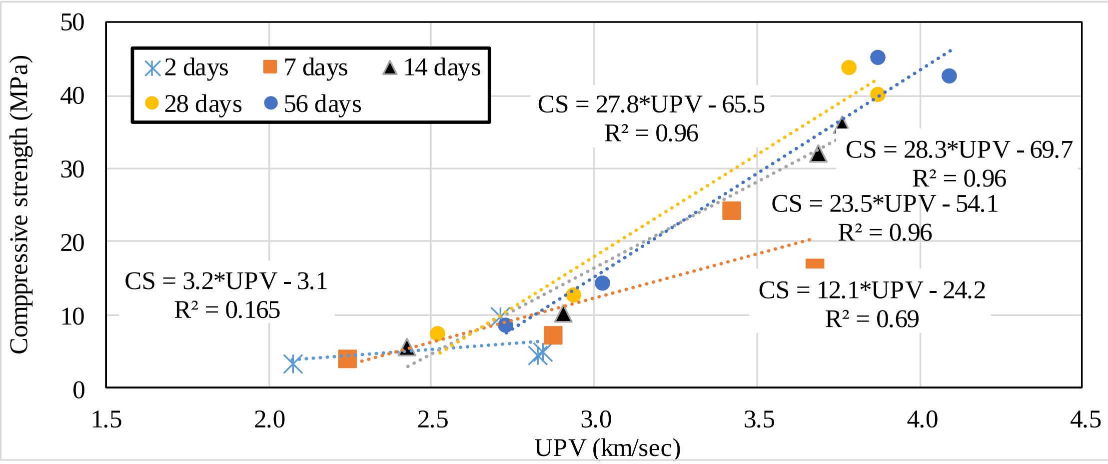


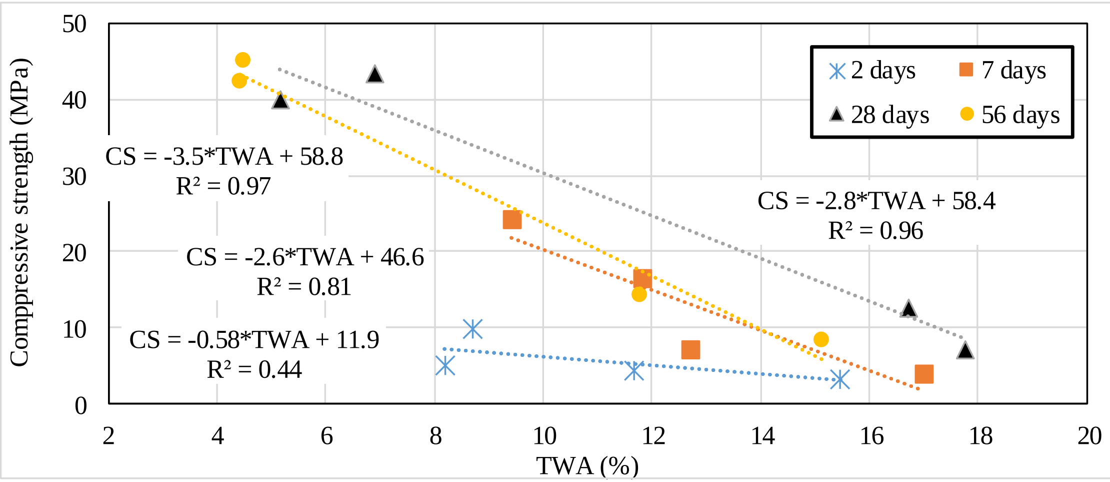
Fig.9: a) CWA coefficient results, b) % increase in CWA versus amount of MSWI-BA

3.6 Correlations between Mortar Properties

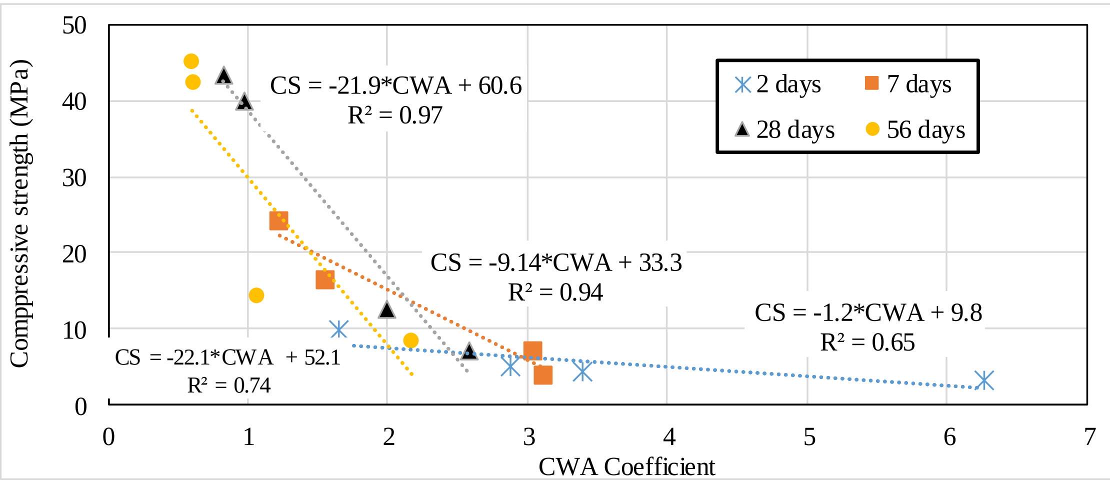
In all engineering, compressive strength is considered a destructive test while UPV, TWA and CWA are not. In order to reduce the number of trial tests and to secure the desired properties, researchers have expressed interest in developing regression models between compressive strength, UPV, TWA and CWA. Since each mix contains several parameters and each parameter has different variability, those relationships don't have a general pattern (IAEA 2012, Mahure 2011, Prassianakis 2003). However, in this work, the connections between compressive strength, UPV, TWA and CWA were explored. Fig 10 displays the relationship between those tests at all curing duration and best-fit formula was performed using linear regression analysis. As shown in Fig 10a, the compressive strength and UPV draws near a linear relationship and the coefficient of determination R^2 is 0.16, 0.69, 0.96, 0.96 and 0.96 at 2, 7, 14, 28 and 56 curing days respectively. Data analysis shows the high correlation between compressive strength and UPV at all ages except at 2 days. This may be due to a measurement error in the UPV values for the control sample at 2 days. The high value of the coefficient of determination at other ages reflects the strength of the relationship and is consistent with the general understanding that high UPV values indicate high quality mortar with minimum amount of voids. A second correlation performed between the compressive strength and TWA at 2, 7, 28 and 56 days is presented in Fig 10b. A general negative correlation exists between the compressive strength and TWA. In other words, an increase in TWA is associated by a drop in compressive strength. Obviously, the relationship is solid (R^2 is 0.44, 0.81, 0.96 and 0.97 at 2, 7, 28 and 56 curing days respectively). At 56 days, TWA was lowest as an increase in curing yields less porous microstructure and therefore higher compressive strength. On the other side, it is to be noted that TWA was highest at 2 days as less curing generates lower strength mortar. A third relationship was established between the CWA and the compressive strength. The resulting correlation coefficient (R^2) varied between 0.74 and 0.97, indicating a strong correlation (Fig 10c). Similar to TWA, the relationship between CWA and compressive strength is inversely proportional. A raise in CWA is accompanied by a decrease in compressive strength and vice versa. Such result is consistent with current literature (Machaka et al. 2019). It should be note here all equations presented in Fig 10 are case specific to this study as the compressive strength, UPV, TWA and CWA depend on many factors such as cement-mortar paste content, water cement ratio, size of specimen and amount of MSWI-BA.



(a) Compressive strength – UPV correlation.



(b) Compressive strength – TWA correlation.



(c) Compressive strength – CWA correlation.

Fig.10: Correlations between the compressive strength and a) UPV, b) WA and c) CWA

4. CONCLUSIONS

This paper is part of a research project to investigate the use of MSWI-BA as a partial replacement [25%, 50% and 100%] of sand in mortar specimens. This was achieved through a series of laboratory tests: compressive strength, UPV, density, TWA and CWA. Based on this study, the following conclusions can be drawn:

- The incorporation of MSWI-BA at the 25% replacement level yield the highest compressive strength among other mixes after two weeks of curing. This was attributed to a better compactibility of the mix at this replacement level and to the pozzolanic reaction. However, the strength decreases 55% to 80% when the amount of MSWI-BA is increased from 25% to 50% and 100%.
- The UPV values for mixes containing 50% and 100% sand replacement by MSWI-BA fall in the 2-3 range for all curing durations indicating poor mortar quality. On the other side, replacing 25% of sand by MSWI-BA generates satisfactory UPV values.
- The use of MSWI-BA beyond the 25% replacement level significantly increases the TWA and the CWA yielding a weaker and pervious mortar matrix.
- Test analysis indicates strong correlation between compressive strength, UPV, TWA and CWA at 7, 28 and 56 curing days.
- Finally, it can be stated that replacing natural sand by MSWI-BA at the 25% replacement level can be a useful strategy to decrease landfill material and virgin aggregate consumption. Any replacement level above the threshold of 25% results in serious reduction in mortar properties.

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