3rd International Conference on Bio-Based Building Materials

June 26th - 28th 2019
Belfast, UK

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

H. Ghanem[1], M. Machaka[1], J. Khatib[1*], A. Elkordi[1], O. Baalbaki[1]
[1]School of Engineering, Beirut Arab University, Beirut, Lebanon
*Corresponding author; e-mail: j.khatib@bau.edu.lb

Abstract
Municipal solid waste is currently a pressing challenge in Lebanon. This problem has been aggravated recently due to an increase in population resulting from the flow of Syrian refugees to the country. Incineration is a common technique to treat the solid waste resulting in the formation of a well-known residue: Municipal solid waste incineration bottom ash (MSWIBA). Those residues can be either dumped in landfills leading to environmental concerns or used in construction materials as a sustainable, resource efficient and economic approach in both solid waste management and construction. The goal of this study is to explore this option. For this purpose, mortar specimens were prepared with amounts of 10, 20, 30 and 40% weight of cement replaced by MSWIBA obtained from incinerators. Three tests (compressive strength, ultrasonic pulse velocity (UPV) and total water absorption (TWA)) were performed for each mixture at different curing durations: 1, 3, 7, 14 and 28 days. Results indicate that MSWIBA has a limited cementitious activity and a deleterious effect on the compressive strength of mortar cubes. From the analysis of the pozzolanic activity index, it was found that the maximum replacement of cement by MSWIBA should be limited to 10%. UPV results show that the curing duration is of paramount importance for the mortar quality and any increase in the MSWIBA beyond the 10% replacement level leads to significant drop in the UPV results. Finally, the evaluation of TWA results indicates the presence of MSWIBA in mortar is not the main factor affecting its absorption.

Keywords: Municipal Solid Waste, Mortar, Bottom Ash, Compressive strength, Absorption, curing durations.

1 INTRODUCTION

Waste generation is a global problem. This forced governments throughout the world to develop strategies in order to reduce and reuse the amount of waste generated. Many types of waste such as; residues from coal power station, steel industry, demolition sites, can be used in the production of construction materials (Baalbaki et al. 2018; Charbaji et al 2018; El-Darwish *et al., 1997;* El-Kurdi *et al*., 2014; Ghanem et al., 2019; Hadjsadok *et al*., 2012; Herki and Khatib, 2013; Herki and Khatib, 2016; Khatib *et al*., 2008; Khatib *et al*., 2009; Khatib *et al.* 2013a; Khatib *et al.* 2013b; Khatib *et al.* 2014; Khatib *et al*., 2015a; Khatib, 2016 ; Khatib *et al*., 2016; Mangat *et al*., 2006; Okeyinka *et al*., 2015b; Sonebi *et al*., 2016; Wright and Khatib, 2016). The generation of waste is currently on the rise in Lebanon as the population and the economic growth continues to increase. Based on data generated in 2013, Lebanon produces annually 2.04 million tons of Municipal Solid Waste (MSW) (Massoud et al. 2016). This amount is dependent on human activities and environmental awareness. The MSW is expected to increase by 1.65% each year. MSW in Lebanon is composed of 16% paper; 11.5% plastic; 5.5% Metal; 3.5% glass and 52.5% organic waste. 48% of the MSW are landfilled, 29% dumped, 15% composted and 8% recycled. Over the last few years, the number of Syrian refugees has increased dramatically resulting in an enormous MSW. Consequently, waste management has become a challenging problem for the government that needs to be urgently solved.

As stated above, in Lebanon, landfill and dumping the MSW are the main ways of disposal. However, as the available land dwindled gradually and as the MSW contains unsafe elements such as heavy metals, it becomes vital to look for other alternatives. The incineration technique can reduce the MSW by 70% by mass and 90% by volume while achieving the objective of heat recovery (Lynn et al 2017). For those reasons, incineration technology is gaining popularity. As a consequence of the incineration process, two by-products are produced: (municipal solid waste incineration (MSWI) bottom ash (BA) and fly ash (FA)).

MSWI-BA is a residue generated from the bottom of the combustion chamber and represents approximately 20 to 30% by weight of MSW (Becquart et al 2009). They are large particles that have similar appearance to silty sand and gravel with small amount of unburnt organic materials (Siddique 2010). It is considered nontoxic. On the other side, MSWI-FA is considered hazardous and contains significant 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). Besides, MSWI-FA contains higher levels of soluble salts than MSWI-BA (Wongsa et al 2017; Jiang et. al 2009). For the all the above reasons, MSWI-FA is not allowed to be used as construction materials in most countries (Bertolini, L et al 2004; Aubert, J et al. 2004).

Cement manufacturing and industry has a long history of absorbing and recycling of wastes of different types (An, et al 2015). In fact, this will provide several interesting alternatives for the construction industry to use industrial by-products and wastes as raw materials such as blended cement. Many countries have tried to beneficially use the MSWI-BA in cement-based products. Some studies have focused on using MSWI-BA as a partial replacement of aggregate in concrete, but concluded that it was not a suitable material (Berg and Neal 1998). Other researchers have used MSWI-BA as partial replacement of cement in mortar but their results were not conclusive (Jaturapitakkul et al. 2003; Pan et al. 2008). Although considered non-hazardeous, its uncertainty regarding its engineering behavior has been a serious barrier in promoting its useful use as a technology material. If proven that MSWI-BA possesses binding properties, it will lead to a reduction in the production of cement which greatly benefit the environment because of the diminution of CO_2 emissions. This is in addition to the reduction in natural raw materials associated with the production of cement. The aim of this study is to explore the possibility of using MSWI-BA as a partial replacement of cement in mortar specimens. Conclusions derived from this study are expected to be the basis for the safe utilization of MSWI by-products; therefore contributing to the sustainability of the cement industry.

2 EXPERIMENTAL STUDY

2.1 Materials

The cement used in this study is ordinary Portland Cement type I obtained from SIBLIN plant located in the mount-Lebanon. The cement complies with all requirements according to Libnor NL53. MSWI-BA was received in the laboratory in a powder form and obtained from an incineration plant located in the Bekaa Valley. For the replacement of cement in the mortar, the BA was oven dried at 100C for 24 hours and then smashed under dry conditions. Sand used in the mixtures was from the Dibbieh area and has fineness modulus of 2.7. The particle distribution of sand met the requirement of ASTMC33. Drinking-quality water was used in all mortar mixtures. Due to the nature of the investigation, a moderate degree of workability was targeted. Thus, no superplasticizers was included in the mixtures.

2.2 Mix Designs

Five mortar mixtures were conducted in this study. Of the five mortar mix designs, four contain different replacement percentage of cement by MSWI-BA (10%, 20%, 30% and 40%). The fifth mix does not contain MSWI-BA acting the role of a control sample. The water cement ratio for all mixtures was fixed at 0.38 and the ratio of sand to cement was equal to 3. Air entrained is added to obtain a 2% air in the mixtures. For each mix, two replicate specimens were casted for each test conducted. The total number of specimens tested is 75. The mixture design information is presented in Tab. 1.

2.3 Sample Preparation

Once the material are measured based on their proportions, they were placed in the paddle and bowl mixer in the following sequence as stated in ASTM C305. First, the mixing water is decanted into the bowl. Second, cement and MSWI-BA are mixed together and added to the mix. The mixer is switched on for 30 seconds at slow speed (140 ± 5 rpm). Then, the whole amount of sand is added gradually 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 a 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 is switched on for a final 60 seconds at medium speed. To check the workability of the mortar, immediately after the mixing procedure is over, a small amount of mortar is placed on the flow table to determine the flow of the mortar. The test is conducted according to ASTM C1437. From the caliper measurements, the flow of mortar for all mixtures was found to be in the range of 95-105% indicating good workability. Following the flow test, the mortar was directly poured into the molds. For the compressive strength, standard steel cubic molds, 50×50×50 mm are used according to ASTM C109. For the ultrasonic pulse velocity and total water absorption tests, standard cubes specimens with internal dimensions 100×100×100 mm are used as shown in Fig. 1.

Fig. 1. Mortar specimens.

3 RESULTS AND DISCUSSION

The results of the compressive strength, UPV, TWA tests, data analysis and the correlation between the three tests for mixtures containing 10%, 20%, 30% and 40% MSWI-BA will be presented in the following sections. A short description of each test procedure will be provided as well.

3.1 Compressive strength

The compressive strength of mortar is known as a measure of mortar quality. It is a destructive test where 2 inches mortar cubes are subjected to compressive forces at a rate of 1.4 kN/sec until failure. The compressive strength of mortars depends on many factors: mix proportions, water cement ratio, curing, etc. The results of the compressive strength of 100×100×100 mm cubes are presented in Fig. 2 and 3. Those figures display a set of relations between the compressive strength of cubes and the curing duration for mixtures containing different amount of MSWI-BA. As shown, all plots display similar characteristics pattern. Compressive strength increases as curing durations increase and this is irrespective of the amount of MSWI-BA in the mixture. For example, for mix 3 holding 20% MSWI-BA as partial replacement of cement, the compressive strength for mortar cubes are is 1.24, 4.3, 13.1, 14.5 and 19.9 MPa for 1, 3, 7, 14 and 28 days curing. The results are very much expected.

Tab. 1: Details of 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	0.38	270	335.7	0	1008
2	10	0.38	270	302.1	33.5	1008
3	20	0.38	270	268.6	67.1	1008
4	30	0.38	270	235.7	100.7	1008
5	40	0.38	270	201.4	134.2	1008

The volume of the main hydration products; calcium silicate hydrate (C-S-H) and calcium hydroxide (CH) produced from the hydration of tricalcium silicate (C3S) and dicalcium silicate (C2S) go up as curing period is increased. This will eventually lead to the reduction of capillary pores resulting in a more compact structure and ultimately higher compressive strength. Several other important observations can be deducted from the plots. The compressive strength of the control mixture displays the highest strength among all mixtures and the relationship between the percentages of MSWI-BA in mortar and the compressive strength is inversely proportional. In other words, as the % MSWI-BA increases in the mixtures, the compressive strength of mortar cubes goes down and this can be noticed for all curing durations. For example, for a curing period of 14 days, the compressive strength for the control mixture is 22.5 MPa whereas it is 17.69 MPa for the mixture containing 10% MSWI-BA. Similarly, the strength continues to decrease to 14.5, 11.3 and 9.3 MPa for mixtures comprising 20%, 30% and 40% MSWI-BA respectively. Therefore, one can deduct that the addition of MSWI-BA to mortar is detrimental to the compressive strength. One possible explanation is that the presence of MSWI-BA with cement alter the nature of the hydration phases. Partial replacement of cement by MSWI-BA reduces the proportion of primary reactants C3S and C2S resulting in insufficient formation of C-S-H leading to a drop in the mechanical strength. Although the above finding indicates that the addition of MSWI-BA to the mixture will not promote strength but will only bring dilution effect to the hydration system and retard the cementitious reaction, it is important to determine precisely the % decrease in compressive strength for all mortar mixtures at all curing duration as this will allow concrete technologists determine the maximum permitted amount of MSWI-BA in mortar. Results of the analysis are shown in Fig. 4. At the early ages (1, 3 and 7 days), the % decrease in compressive strength is very significant. For example, at one day, the drop for mixtures having 10%, 20%, 30% and 40% MSWI-BA is 20%, 35%, 56%, and 79% respectively. This is a clear indication that pozzolanic reaction of bottom ash is almost nonexistent at early ages. On the other side, at 28 days curing, those drops are significantly reduced to 9%, 19%, 29% and 36% respectively. Although none of the mixtures containing MSWI-BA compressive strength topped the one of the control specimen, results indicate that some sort of pozzolanic activity took place. Pozzolanic reaction requires the presence of CH from the hydration of portland cement. At early ages, CH was not available. After 3 weeks, the reactive silica in MSWI-BA react with CH to form secondary C-S-H and calcium aluminate hydrate (C-A-H) possessing cementitious properties. To determine the quality and exact amount of MSWI-BA allowed in the mixtures, the pozzolanic activity index (PAI) needs to be determined. According to ASTM C311 and C618, samples with PAI greater than 75% at 28 days are considered to have a positive PAI. Fig 5 displays the PAI for all mixtures at all curing durations. As shown, mix 2 holding 10% MSWI-BA replacement level has PAI of 80%, 76%, 84%, 78% and 91 at 1, 3, 7, 10 and 14 days respectively. The PAI values for other mixtures decrease steeply below the minimum threshold of 75% as the % MSWI-BA increases from 10 to 20%, 30% and 40%. Consequently, based on the PAI results, although possessing limited pozzolanic activity, MSWI-BA can be considered as cementitious supplementary material by the concrete manufacturing industries if the cement replacement levels by MSWI-BA does not exceed 10%.

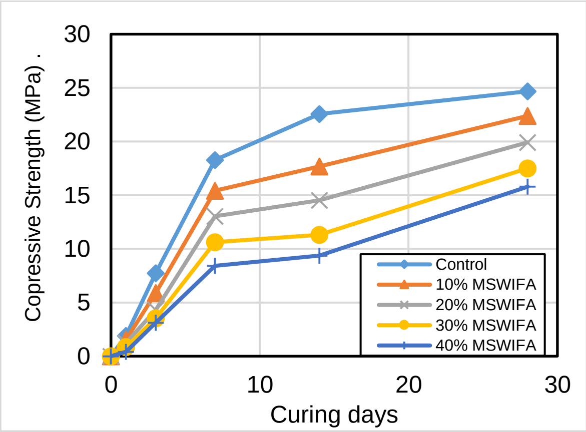

Fig 2 Effect of curing duration on compressive strength.

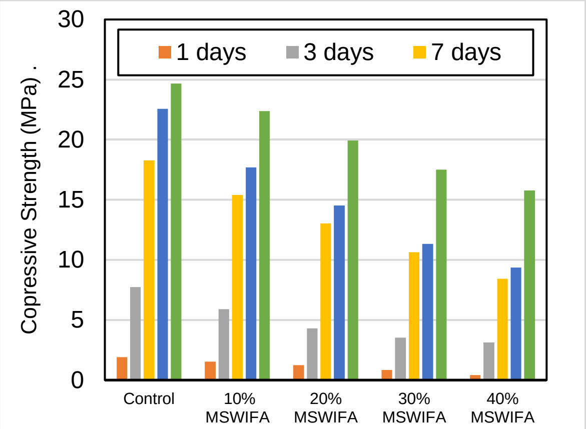

Fig. 3 Effect of MSWI-BA on compressive strength.

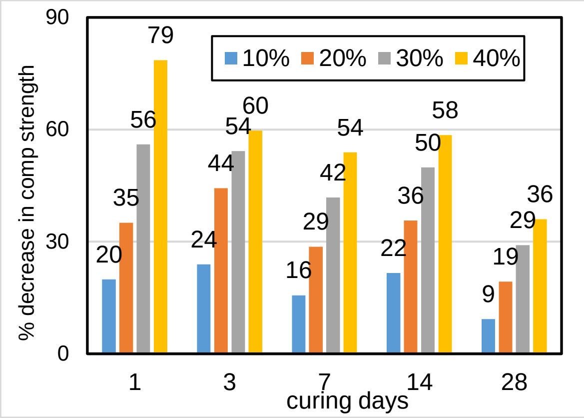

Fig. 4 % decrease in compressive strength.

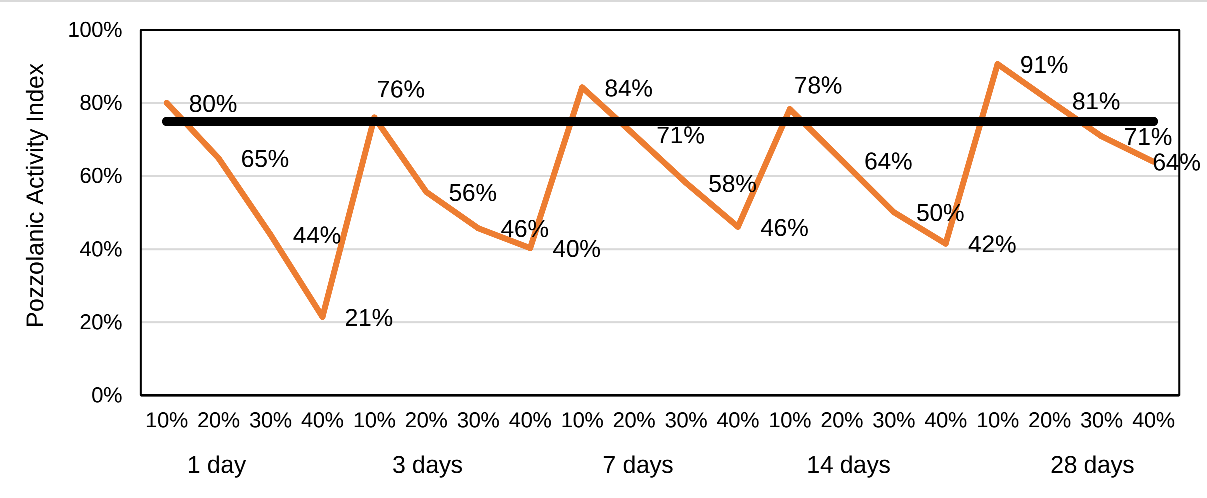

Fig 5. Pozzolanic activity index for the various mixes.

3.2 Ultrasonic pulse velocity tests

The ultrasonic pulse velocity (UPV) test is a nondestructive test to check the quality of concrete. This procedure consists of measuring the velocity of an ultrasonic pulse wave that pass through the concrete structure. It has been standardized as "Standard Test Method for Pulse Velocity through Concrete" (ASTM C 597, 2016).

Table 2 provides the classification of concrete based on the pulse velocity [IAEA 2012]. A shown in the table, higher velocity indicates higher concrete quality in terms of density, uniformity, etc. whereas lower velocity points to low quality in terms of cracks, defects, presence of voids and other discontinuities.

Tab. 2 Classification of the quality of concrete on the basis of pulse velocity [IAEA 2012]

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

In this study, the UPV test was conducted on all mortar samples at all ages. Results are presented in Fig. 6. Several interesting observations can be made. First, Mix 1 (control sample) yields higher UPV values than mixes containing MSWI-BA. Therefore, one can conclude that MSWI-BA affect negatively the quality of mortar. This may be due to the fact that the presence of MSWI-BA in the matrix leads to the creation of voids resulting in lower UPV values. Second, it can be seen that the relationship between the UPV results and amount of MSWI-BA is inversely proportional. For example, the UPV results are 4.52, 4.24, 3.09, and 2.81 km/sec for mixtures containing 10%, 20%, 3% and 40% MSWI-BA respectively. This is an indication that the presence of MSWI-BA beyond the 10/20 percent reduces significantly the quality and uniformity of mortar. One possible explanation is that the volume of voids between MSWI-BA particles increase as the amount raises. Third, almost all UPV results for mixtures 4 (30% MSWI-BA) and 5 (40% MSWI-BA) at all curing duration fall below 3 km/sec classifying effectively the mortar as poor. One possible reason for this behavior is that the MSWI-BA plays the role of a filler material in the mortar matrix and contribute to the hydration process in a very limited scale. Fourth, as curing duration increases, UPV values goes up and this is irrespective of the amount of MSWI-BA in the mixtures. This last point is very expected as the moisture level play an important role during hydration leading to the development of hydration product contributing to the strength and uniformity of mortar. Thus the higher UPV values. Lastly, from all mixtures incorporating MSWI-BA, mix 2 (10% MSWI-BA) at 28 days generates the highest UPV value (4.52) indicating excellent mortar quality.

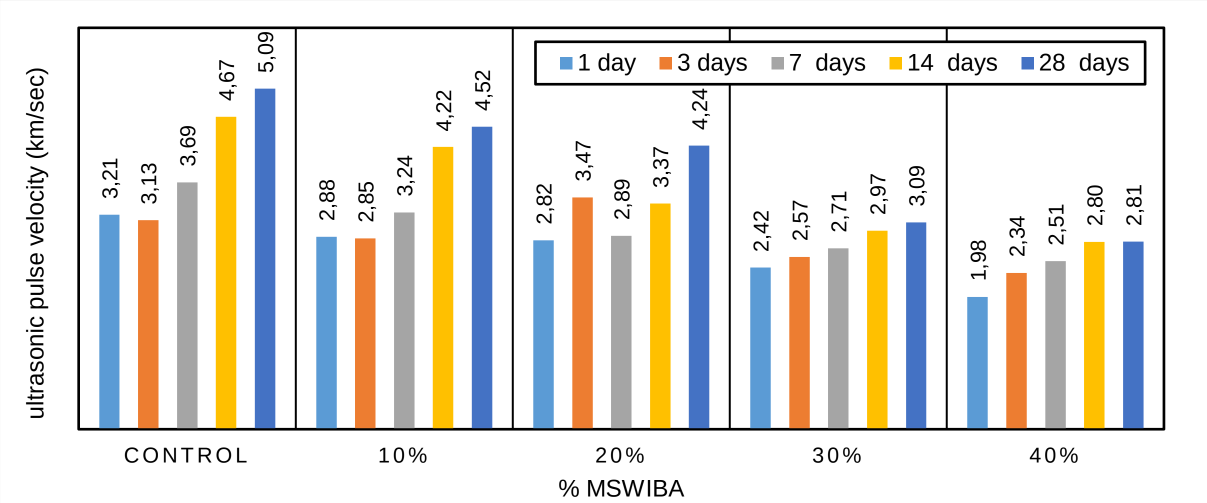

Fig. 6 UPV for the various mortar mixes.

3.3 Total water absorption (TWA)

The TWA is a nondestructive test conducted on mortar/concrete samples to measure the amount of water absorbed after a specific period of time. It can be considered a relevant parameter that can be related to the performance of mortar. The TWA depends on many factors: mixture proportions, curing duration, air content, presence of chemical admixtures and supplementary cementitious materials, etc. Following 7, 14 and 28 days of curing, the mortar specimens are placed in oven at 80C for 48 hrs until a constant mass is reached. Afterwards, the cubes are totally immersed in water for 24 hrs and the TWA is determined accordingly. Results are presented in Fig. 7 and 8.

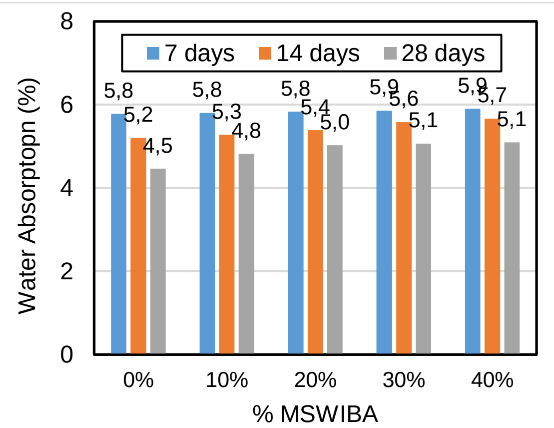

Fig. 7 Effect of MSWI-BA on TWA.

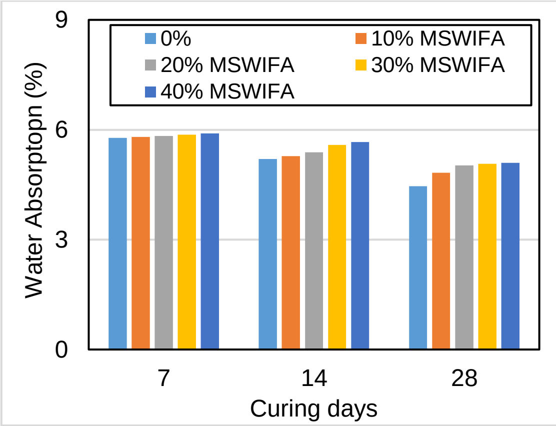

Fig. 8 Effect of curing durations on TWA.

Many remarks can be noticed. For 14 and 28 days, the TWA goes up as the % of MSWI-BA increases. For example, at 28 days, the TWA is 4.5%, 4.8%, 5%, 5.1% and 5.1% for mixtures containing 0%, 10%, 20%, 30% and 40% MSWI-BA respectively. This is equivalent to a 6.6%, 4.1%, 2% and 2% increase for each 10% increment of MSWI-BA In an expectant manner, the control specimen displays the lowest TWA (4.5%) but the other mixtures show higher TWA values. It is well known that MSWI-BA has a high amount of fine particles leading to a much higher surface area and therefore contributing to higher water absorption. Consequently, as the amount of MSWI-BA particles increase in the mixtures, the TWA raises as well reducing the amount of water available to react with cement in the mortar. That can explain as well the significant drop in compressive strength for mixtures holding 20%, 30% and 40% MSWI-BA. It is interesting here to note the TWA values for all mixtures remain almost constant at 7 days curing. Thus, it can be deducted that the presence of MSWI-BA is not the main factor affecting mortar absorptions properties. From the plots, it can be shown that the effect of curing on TWA are pretty significant. For example, for mix 2 (10%MSWI-BA), the TWA is 5.8% at 7 days curing whereas it is 5.3% and 4.8% at 14 and 28 days respectively. This is equivalent to 9.4% and 10.4% decrease. This can be easily explained as follows: as water absorption reflects the porosity of the matrix, the increase in curing leads to the capillary pores in the mortar being filled with water resulting in a reduction of water absorption with time.

3.4 Test correlations

As mentioned previously, the compressive strength test is destructive test whereas the UPV test is not. Therefore, researchers have shown interest in the past to explore the relationship between the compressive strength and UPV. Because of the variability in the mixture design, those relationships do not have a general pattern and the strength of mortar/concrete mixtures can't not be determined accurately [IAEA 2002, Prassianakis 2003, Mahure 2011]. However, in this study, we have explored the connections between compressive strength and UPV. Fig. 9 illustrates this relationship at all curing ages and a general best fit formula is developed. As shown, the compressive strength increases with UPV and draws near a linear relationship and the coefficient of determination R2 is 0.97, 0.25, 0.97, 0.97 and 0.96 at 1, 3, 7, 10 and 14 curing days respectively. Data analysis indicates a very high correlation between UPV and compressive strength at all ages except at 3 days. This is possibly due to a measurement error of the UPV value for mix 3 (20% MSWI-BA) at 3 days. The high correlation at other ages (1, 7, 10 and 14 days) are consistent with our understanding that high UPV values indicate high quality concrete with minimum amount of voids which corresponds to higher compressive strength. Another correlation was performed between the TWA and the compressive strength at 7, 14 and 28 days. Results are presented in Fig 10. As shown, a general negative correlation exits between TWA and compressive strength. A decrease in TWA is accompanied by a corresponding increase in compressive strength. Clearly, the relationship was very strong (0.99 at 7days, 0.94 at 14 days and 0.84 at 28 days). At 28 days, the TWA was the lowest as more curing means less voids and thus higher compressive strength and more durable mortar. On the other side, TWA was highest at 7 days, as less curing period implies more voids and less hydration contributing to lower strength. It should be mentioned here that the relationships shown in Fig 9 and 10 are case specific to this study as the UPV, compressive strength and TWA depend on many factors such as cement-mortar paste content, water cement ratio, size of specimen and amount of MSWI-BA.

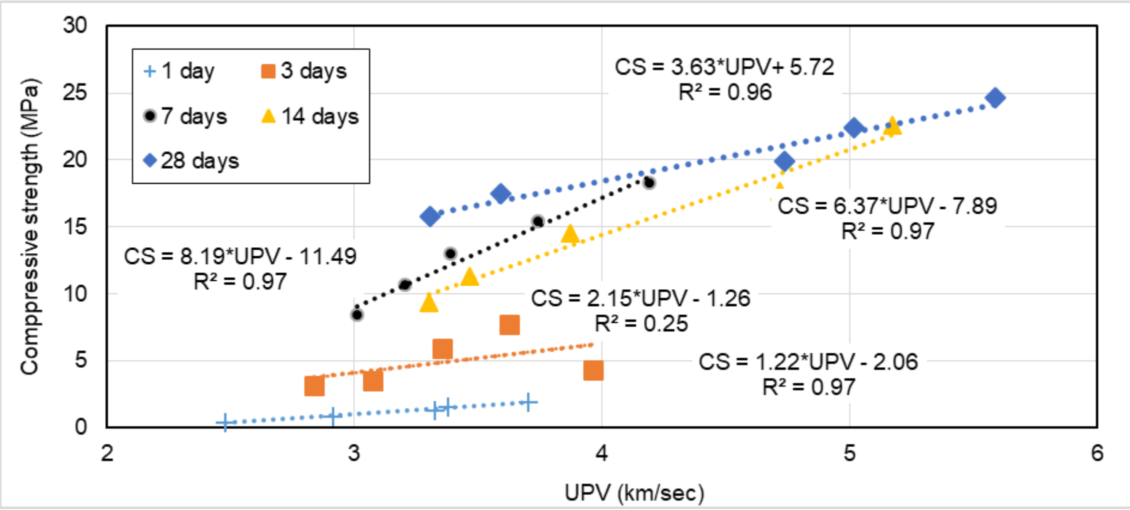

Fig. 9 Correlation between compressive strength and UPV.

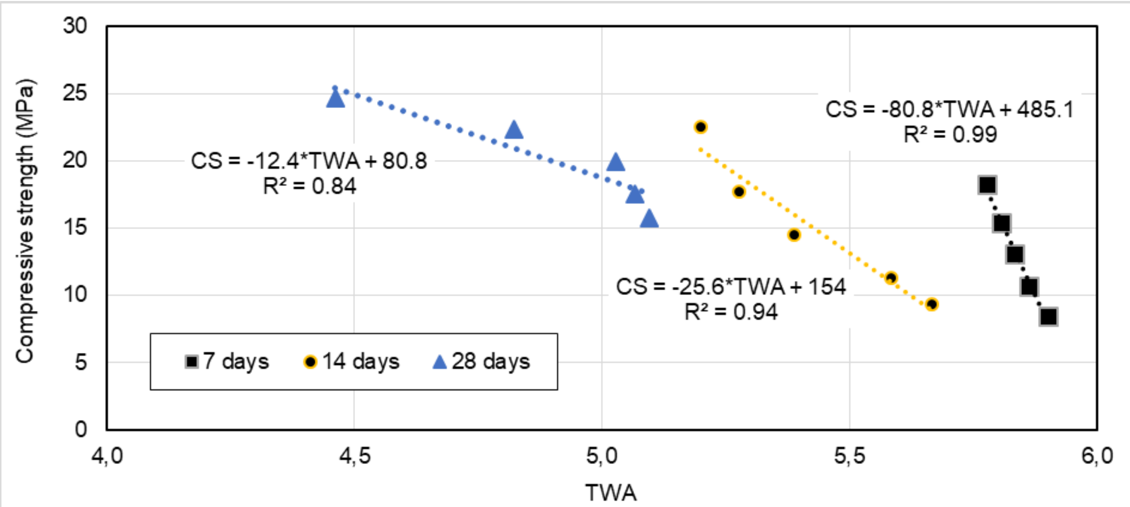

Fig. 10 Correlation between compressive strength and TWA.

4 CONCLUSIONS

In this research, the potential use of MSWI-BA as a partial replacement in mortar specimens was investigated through a series of laboratory tests: compressive strength, UPA and TWA. Based on the work conducted, the conclusions made below would be a step forward toward the development of design guidelines for the use of MSWI-BA. The presence of MSWI-BA greatly reduces the compressive strength as its percentage replacement of cement increases from 10% to 40%. It was found as well that MSWI-BA possesses limited pozzolanic activity and its amount should not exceed 10%. Regarding UPV results, it was shown that curing duration is a major factor in assessing mortar quality and the presence of MSWI-BA beyond the threshold of 10%-20% dramatically decreases its quality. On the other side, the utilization of MSWI-BA in mortar at different levels was not the found to be the major factor affecting its absorptions properties. Data analysis of all tests presents a high correlation between the compressive strength and the UPV and between the strength and TWA.

5 RECOMMENDATIONS

In future research, effort should be made to conduct durability tests such as sulfate attack and alkali aggregate reaction on mortar samples containing MSWI-BA. Different treatment methods of MSWI-BA before use in mortar can be also a point to be investigated.

6 ACKNOWLEDGEMENT

The authors gratefully acknowledge the assistance at Beirut Arab University. Another thanks goes to the plant who provided the MSWI-BA.

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