DAMAGE OF SILICA FUME AND GROUND GRANULATED BLAST FURNACE SLAG MORTARS DUE TO HEAT CYCLES

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ABSTRACT

In this investigation, mortar samples with no pozzolanic material or with 5, 10, 15, 20% silica fume or 30, 50 and 70% ground granulated blast furnace slag were subjected to twice daily heat cycles between room temperature and 65 °C for 90 days. The effect of the heat cycles on moisture loss, compressive strength, ultrasonic pulse velocity and drying shrinkage was assessed. The inclusion of pozzolanic materials in the heat cycled mortars increased moisture loss and reduced the compressive strength in all but the 5 and 10% silica fume mortars. The ultrasonic pulse velocity was affected to various degrees, whereas the observed shrinkage values for pozzolanic mortars after exposure to heat cycles were excessive.

الملخص العربي:

في هذا البحث تم تعريض عينات من مونة الأسمنت البوتلاندي العادي أو المحضرة من احلال جزء من الأسمنت البورتلاندي بغبار السليكا بنسبة ٥، ١٠، ١٥ أو ٢٠% أو احلال جزء من الأسمنت بخبث الأفران بنسبة ٣٠ ، ٥٠ أو ٧٠% لدورات حرارية بين ٦٥ ° م لمدة ٧ ساعات تليها درجة حرارة الغرفة (٢٣±٣ ° م) لمدة ٥ ساعات و ذلك لمدة ٩٠ يوما لمعرفة أثر هذه الدورات الحرارية على عدة خواص للمونة مثل فقدان الرطوبة، مقاومة الضغط، سرعة الموجات فوق الصوتية و الانكماش بالجفاف. و أظهرت النتائج أن فقدان الرطوبة من عينات مونة الأسمنت البوتلاندي العادي بلغت ٧,٣% بالوزن خلال مدة الدورات الحرارية. أما المونة المحتوية على غبار السليكا فقد و صلت نسب فقدان الرطوبة إلى ٩,٢، ٩,٧، ١٠,٧ و ١١,١ % و ذلك للعينات التي تحتوي

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على ٥، ١٠، ١٥، و ٢٠% من غبار السيليكا ، على التوالي. كذلك بلغت نسب فقدان الرطوبة ١١,١، ١٢,٨ و ١٣,٧ % للعينات التي تحوي خبث الحديد و ذلك لنسب خبث ٣٠، ٥٠ و ٧٠% ، على التوالي. وجد كذلك أن الدورات الحرارية أدت إلى خفض مقاومة الضغط في جميع العينات بنسب متفاوتة فيما عدا العينات التي تحتوي على ٥ و ١٠% من غبار السليكا و التي يعتقد أن التفاعلات قد نشطت فيها بفعل حرارة الفرن مما أدى إلى تحسن المقاومة. و بتحليل نتائج سرعة الموجات فوق الصوتية وجد أن الحرارة أدت إلى خفض السرعة بدرجة أكبر في العينات المحتوية على بدائل الأسمنت ماعدا العينات بنسبة ١٠% غبار سيليكا أو ٣٠ و ٥٠ % خبث الحديد. و ظهر كذلك أن عينة ١٠% غبار السيليكا تفقد سرعة الموجات فوق الصوتية بدرجة أبطأ من العينات الأخرى مما يدل على تحملها للحرارة بصورة أفضل من غيرها من العينات المختبرة. و بقياس الإنكماش بالجفاف ظهر أن عينات غبار السيليكا زاد فيها الإنكماش بمقدار ١٢٠، ٣٠٠، ٣٢٠ و ٤٨٠% مقارنة بذلك المقاس لعينات الأسمنت البورتلاندي العادي أما عينات الخبث فقد وصل الإنكماش إلى ٢٨٠ و ٦٠٠% من ذلك المقاس لعينات الأسمنت البورتلاندي العادي. أما عينة الخبث بنسبة ٧٠% فقد استمرت في الإنتفاش و التمدد طوال مدة التعرض للدورات الحرارية.

INTRODUCTION

Hot dry conditions exist in many parts of Africa, Asia, Australia, and north and south America. These conditions are characterised by a mean annual temperature of 28 °C, with the shade temperature in the summer occasionally approaching 50 °C and can fall in the winter to as low as 5 °C near the coast, or even 0 °C inland. The daily temperature fluctuations may be as high as 30 °C. The level of solar radiation is very high, because of the clear summer skies, and this increases the temperature of the exposed surfaces considerably [1]. It has been reported that the surface temperature of concrete may be as high as 70 °C during hot summer days [2]. These conditions cause severe distress to concrete structures leading to cracking which promotes chemical attack and/or reinforcement corrosion and eventually premature deterioration.

In the search for more durable structures, investigators reported the superior performance of pozzolanic materials under high temperature conditions. For example, Mirza et al. [3] subjected paste, mortar and concrete samples, made with either ordinary Portland cement (OPC) or OPC blended with ground granulated blast furnace slag (GGBS), powdered tuff or silica fume (SF), to water curing at 25 °C or air curing at 35 or 50 °C after 24 hours in a moist room. The samples were maintained in these conditions for up to 300 days. They reported that the samples with cement blends generally showed a lower strength when tested at or before 28 days, but their strength at later ages was higher than the OPC specimens, particularly when cured at 35 or 50 °C. In addition, these samples showed a better resistance to the detrimental effect of prolonged exposure to high temperatures. On the other hand, Robins et al. [4] subjected GGBS concrete to heat and humidity cycles between 43 ± 2 °C, 25-30% RH and 10 ± 2 °C, 70-75% RH. They reported that the 50% GGBS replacement exhibited superior properties compared to OPC under these conditions provided that moist curing is initially applied. Similar investigations by Austin et al. [5] also showed the sensitivity of GGBS concrete to poor curing in arid climates. Moreover, Cabrera et al. [6] found that OPC mortars subjected to hot dry environments (45 °C - 30% RH) suffered severely regardless of the length of moist curing period, whereas pozzolanic mortars moist cured for one day or more exhibited better properties than equivalent mortars cured at normal temperatures. Other investigators [7] placed concrete samples, with and without SF, GGBS or a natural pozzolan called trass, after standard curing in the Gulf region where they were either submerged, subject to wetting and drying or kept on the coast. They reported that all mixes with pozzolans showed better performance than the OPC ones.

As a result of a number of research reports, such as those discussed above, many design codes in the Middle East today specify minimum amounts of SF, fly ash or GGBS along with the traditional recommendations for minimum cement content, minimum cover, and maximum w/c ratio to ensure the durability of concrete [8]. However, the effect of pozzolanic materials on the long term drying shrinkage of concrete is controversial even when tested using standard shrinkage tests. Mehta [9] clearly stated that concrete containing admixtures, whether chemical or mineral, capable of pore refinement usually show higher drying shrinkage. Indeed, Hooton [10] prepared concrete samples with 0, 10, 15 and 20% SF and having w/c = 0.35. The samples were tested for drying shrinkage in accordance with ASTM C157 in which the samples were stored in lime water for 28 days at 23 °C and then dried at 23 °C - 50% RH for up to 64 weeks. He reported that at 64 weeks, the shrinkage of the 5, 10 and 20% SF concrete was 4, 14 and 18% greater than the OPC counterpart, respectively. At this age, the shrinkage values ranged between 376 to 445 microstrains. Sukswang et al. [11] supported this finding, but other investigators [12- 16] reported contrary results by stressing that SF and/or GGBS have a negligible effect on the drying shrinkage.

The weather conditions in the Middle East dictates that the drying shrinkage tendency of concrete containing pozzolanic materials should be investigated at higher temperatures than those applied in standard shrinkage tests. Lura et al. [17] found that the higher temperatures cause a faster shrinkage rate and faster development of self induced stresses. So far, the published results for drying shrinkage of concrete at higher temperatures are even more puzzling than those reported for tests under moderate temperatures in accordance with most standard shrinkage tests. Alsayed and Amjad [18] prepared w/c = 0.45 concrete samples and exposed them to the field conditions in Riyadh for one year and reported that the rate of shrinkage ranged between 330-456 microstrain. Alsayed [19] studied the shrinkage of high strength concrete (w/c = 0.3) also subject to the field conditions in Riyadh for three years. Control samples were kept in laboratory air for comparison. Unexpectedly, the difference in shrinkage strains for samples stored in the laboratory and field was not significant in his data. Fattuhi and Al-Khaiat [20] reported that the maximum recorded shrinkage for samples exposed to the environment in Kuwait for 400 days was 638, 513 ad 463 micro-strain for OPC, 10% and 20% SF concrete, respectively. They noted that their results were not in agreement with the current understanding of the effect of SF on shrinkage. Other samples, not containing SF, were exposed to the same conditions for up to 726 days giving a shrinkage of more than 1100 microstrain. Kharchi and Chabbi [21] measured the shrinkage of concrete made with gravel, 400 kg/m^3 cement and having w/c = 0.5, prepared in simulated Algerian Sahara temperature of 50 °C. They reported that the drying shrinkage reached 1600 microstrain in these conditions.

It can be seen that the published data on the effect of pozzolanic materials on the drying shrinkage of cement matrices in hot weather conditions is inconclusive. The magnitude of shrinkage to be expected in these conditions is also unclear. Therefore, it would appear that there is a need to thoroughly investigate the drying shrinkage phenomenon, and the distress caused by it, in order to take the results into account when designing concrete structures in hot arid parts of the Middle East. In this investigation, mortar samples with no pozzolanic material or with 5, 10, 15, 20% SF, 30, 50 and 70% GGBS were prepared and subjected to heat cycles between room temperature and 65 °C in an oven to simulate the temperature variations during summer in the Middle East. Two heat cycles were applied every day for 90 days. The effect of this treatment on moisture loss, compressive strength, ultrasonic pulse velocity and drying shrinkage were measured in order to asses the degree of distress in the samples.

MATERIALS, MIX PROPORTIONS AND TESTING PROGRAM

Materials

Ordinary Portland cement (OPC) conforming to ESS 373/1991 [22] was used in preparing the test samples. The fine aggregate was natural sand and conforming to ESS 1109/2002 [23]. Tap water was used in mixing and curing the test specimens. Chemical analysis of the cement, silica fume (SF) and ground granulated blast furnace slag (GGBS) are shown in Table 1.

Mortar Mix Proportions

The mortar mixes in this investigation had a water to cementitious materials ratio of 0.5 and a cementitious materials to sand ratio of 1:2. In the mortars containing SF, 5, 10, 15 or 20% SF partially replaced the cement by weight. In the mortars containing GGBS, 30, 50 or 70% GGBS replaced the cement by weight.

Mixing of Mortars and Sample Preparation

The mortars were mixed in accordance with the method for mechanical mixing of mortar to plastic consistency [24]. From each mortar mix, six 50 mm cubes and three 40 x 40 x 160 mm prisms were prepared. The samples were placed in their moulds under wet burlap covered with plastic sheets for 24 hours. They were then demolded and cured under water for an additional 27 days.

Subjecting Samples to Heat Cycles

After the end of the moist curing period, three cubes from each mortar mix were left in air at room temperature (23 ± 3 °C) undisturbed. The rest of the cubes and prisms were placed in an oven operating a heat cycle simulating the temperature variation in the arid parts of the Middle East during the summer. A timer was used to operate the oven at 65 for 7 consecutive hours. After that the timer switches off the oven for 5 hours, and the temperature in the oven drops to room temperature within one hour. Thereafter, the cycle was repeated. Two heat cycles were applied every day to accelerate the deterioration. The samples were left in the oven for 90 days.

Test Procedures

The cube specimens were tested for compressive strength after 90 days from either being kept at room temperature or subjected to the heat cycles. Before being placed in the oven, the weight, ultrasonic pulse velocity (UPV) and length of the prisms were recorded. At various time intervals, the prism samples were taken out of the oven to monitor their weight (for moisture loss estimation), UPV (internal crack detection), and length changes (for swelling and shrinkage determination). The length of the samples was measured using a vernier calliper.

RESULTS AND DISCUSSION

Moisture Loss

The change in weight, due to heat cycles, for the tested mortars is plotted in Figures 1 and 2 for the SF and GGBS mortars, respectively. The moisture loss from the tested mortars by the end of heat cycles was 7.3 for OPC mortar, 9.2, 9.7, 10.7 and 11.1 for the 5, 10, 15 and 20% SF mortars, respectively. The moisture loss was 11.1, 12.8 and 13.7 % for the 30, 50 and 70% GGBS mortars, respectively. It can be seen that the inclusion of pozzolanic materials increased the moisture loss, and the percentage moisture loss increased with the increase in pozzlolanic materials content. The percentages of moisture lost at different heating times are shown in Figures 3 and 4. For the SF samples, most of the moisture was lost before 7 days, but moisture was still being lost from the samples up to 56 days after being placed in the cyclic heating ovens. However, for the slag mortars, all moisture was lost from the samples before 28 days with most of the moisture being lost before 7 days in cyclic heating. This may be attributed to the fact that in the current investigation, both OPC and pozzolanic mortars had the same water/binder ratio. This would lead to an increased amount of evaporable water in SF mortars compared to the OPC one, because the C-S-H formed during the SF reaction contains less water than that formed from normal cement hydration [25]. As the percentage of SF increases, so would the amount of non consumed water, and in turn this reflected on the higher moisture loss with high SF content. The slag mortars, in which the reaction proceeds more slowly [26], would also naturally contain more evaporable water especially because of diluting the cement with high slag replacement levels.

Aldred [27] found that the weight loss of SF concretes during ambient drying was lower than that observed in the OPC counterpart. They attributed this to the finer pore structure of the SF concrete. However, Bentz and Stutzman [28] found that the pores larger than 16 μm^2, as determined from SEM images, in concrete having w/c = 0.45, up to 20% SF and 50% river gravel was greater in mature SF concrete compared to concrete without SF. This was attributed to the consumption of $Ca(OH)_2$ crystals formed by early cement hydration leaving empty pores behind. They also reported that these pore can percolate to form a network. On the other hand, Li et al. [25] found that the evaporable water content in silica fume pastes increased at later ages and that the pore structure of the SF paste became coarser with time, especially with high SF contents. They attributed these observations to the consumption of $Ca(OH)_2$ by pozzolznic reaction which leads to the instability of the original calcium silicate hydrate (C-S-H) formed from the cement hydration. Under these conditions, some of the C-S-H is decomposed freeing water and leading to coarsening of the pore structure. The authors of the current investigation suggest that heating in the oven had re-activated the pozzlolanic reactions and hence lead to increased pore connectivity, due to the consumption of the $Ca(OH)_2$ crystals, and also increased evaporable water content at later ages, due to decomposition of some C-S-H. This explains the continued moisture loss from the SF mortars of the current study after more than 28 days of being placed in the ovens.

Cabrera et al. [6] found that slag mortars cured at 20 °C temperature, like the ones prepared in the current investigation, had higher permeability and median pore diameter compared to their OPC counterparts after 28 days of moist curing. The reverse was true if initial curing was at higher temperature. Li et al. [29] studied the properties of slag paste prepared using slag having different fineness values, which were prepared by classifying the raw slag in an air classifier to obtain higher fineness slags. They reported that the porosity was increased with the increase in the raw slag content, but the trend was reversed with the finer slags. Jau and Tsay [30], after testing samples with up to 50% slag, reported that the samples with 20% slag had the lowest diffusion coefficient and pore sizes. These observations support and explain the high moisture loss from the slag mortar samples, in the current investigation.

Compressive Strength

Samples kept at room temperature

Figure 5 shows the compressive strength results for the studied mortars. It can be seen that for the samples kept in room temperature the inclusion of SF or GGBS reduced the compressive strength in all mixes except for the mix with 15% SF. Many previous investigations found that the inclusion of SF enhances the compressive strength of cement based matrices. However, usually a superplasticizer is used to aid in dispersing the SF particles in the mix. Austin and Robins [31] found that properties of SF mortars and concrete containing a superplasticizer were superior to those without it. In the current investigation, no superplasticizer was used in the preparation of the mixes, and therefore the strength may have been impaired.

The 15% SF mortar exhibited an increase of 8.7% in compressive strength compared to the OPC counterpart for mortars kept in room temperature. This can be explained by the findings of Yogendran et al. [32 cited in 33] who reported that at a w/c = 0.48, about 15% SF was required to consume all the $Ca(OH)_2$ in concrete (in the current investigation the w/c ratio was 0.5). The absence of large and relatively weak $Ca(OH)_2$ crystals enhances the mechanical properties [34]. Similar findings were reported by Bhanja and Sengupta [35], who also confirmed that the optimum SF% depends on the w/c ratio of the mix. With higher SF percentage (20%), the compressive strength was reduced again. Duval and Kadri [36] observed a similar trend and attributed it to the difficulty in dispersing the large quantity of SF particles.

In general, the GGBS mortars of the current investigation had a lower strength than their OPC counterpart. This agrees with the findings of Jau and Tsay [30], who prepared samples with up to 50% slag, and reported that the strength decreased with the increase in slag percentage. Similar findings were reported by Swamy [37] with slag replacements up to 70%, and w/c ratios ranging between 0.35 – 0.45. It is well documented that, in general cement replacement with slag reduces the strength development of concrete. For example, with 30% slag the strength of pure OPC concrete is achieved after 2 months, with replacements of 50% or more, the OPC strength may be reached after one year or more [38].

Samples subject to heat cycles

Heat cycles had a profound effect on the compressive strength of mortars as can be seen from Figure 6. Most mortars suffered loss in strength, however, the 5 and 10% SF exhibited an increase in strength compared to their counterparts stored in room temperature. The results of the current investigation, for the 0, 15 and 20% SF mortars, are in line with the findings of Saricimen et al. [39], who air cured OPC and 10% silica fume samples (w/c = 0.43) in the laboratory and in the field in the Eastern Province of Saudi Arabia, after 7 days of moist curing. They reported that the inclusion of silica fume increased the strength of the concrete, however, the field cured samples exhibited a reduction in strength compared to their laboratory counterparts. It was reported that high temperature causes micro-cracking in OPC concrete and that deposits of Portlandite and ettringite become concentrated in and around cracks causing loss in strength [40]. In addition, temperature changes cause expansion and contraction of concrete, whereas the moisture loss leads to internal stresses and cracking giving rise to the observed strength loss [41].

The 5 and 10% SF samples exhibited 4.3 and 27.5% increase in strength after exposure to heat cycles, respectively. It would appear that in these mortars hydration and pozzolanic reactions were resumed when the mortars were placed in cyclic heating. The samples were placed in the cyclic heating oven in a saturated state after 28 days of water curing, and it is known that heating encourages chemical reactions (e.g. for every 10 °C increase in temperature the rate of reactions may be doubled [6]). It is expected that such reactions started to take places soon after the samples were placed in the ovens and continued for some time in the inner parts of the samples, where moisture was available. This deduction is based on the work of Baweja et al. [42], who found that in pastes, mortars or concretes containing SF, some un-dispersed SF agglomerates remain even after long periods of curing. These agglomerates can later start to react without damaging the matrix. The same effect was not observed in mortars with higher percentages of SF, probably due to the consumption of $Ca(OH)_2$ by the reactions during early water curing, as discussed above.

The effect of heat cycles on the compressive strength of GGBS mortars is also shown in Figure 6. It should be noted that although the inclusion of slag reduced the compressive strength of the mortars, the loss of strength exhibited by these mortars due to heat cycles was smaller for higher slag contents. This is analogous to the observation of Raheeduzzafar and Al Kurdi [43], who reported that the w/c = 0.6 concrete (low strength) suffered less damage than the w/c=0.4 concrete (high strength) due to heat cycles.

Ultrasonic Pulse Velocity

The UPV results are shown in Figures 7 and 8 for the SF and GGBS mortars, respectively. It can be seen that the initial UPV values for the SF mortars were comparable (i.e. ranging between 3.98 and 4.12), whereas, the UPV values of the GGBS mortars were more diverse (i.e. ranging between 3.35 and 3.88). It is also clear that the heat cycles caused a reduction in UPV values, which depended on the type of mortar and number of heat cycles. It should be noted that Bungey and Millard [44] reported that the UPV of saturated concrete may be up to 5% higher than that for the same concrete in a dry condition. Therefore, the observed UPV loss may be partially due to drying. In general, mortars with higher SF or GGBS contents suffered more UPV loss compared to their counterparts.

Figures 9 and 10 show the percentages loss in UPV at different time intervals due to the heat cycles. In general, the 10% SF, 30 and 50% GGBS mortars exhibited 5.6, 54.2 and 9.8 % lower UPV loss compared to the OPC mortar after the heat cycles, respectively. However, the mortars suffered UPV loss at different rates. The 10% SF mortar lost most of its UPV after 28 days in the cycled oven. This demonstrates that this mortar was more heat resistant than the other tested mortars. The 30 and 50% GGBS mortars ultimately showed a lower percentage of UPV loss compared to the OPC mortar, but most of their UPV was lost before 28 days in the oven.

The authors of the current investigation did not cite any data on the effect of heat cycles on the UPV of mortar samples. Raheeduzzafar and Al Kurdi [43] carried out one daily heat cycle between 60 °C for 4 hours and room temperature on concrete specimens with different w/c ratios. No cement replacement materials were used in their mixes. After 120 heat cycles, during 120 days, the w/c = 0.5 samples lost 8.26% of their initial UPV. In the current investigation, the control mortar samples, which had the same w/c ratio, lost 9.18% of its initial UPV after 56 days or 112 heat cycles. Comparison between the results of the current investigation and that of Raheeduzzafar and Al Kurdi [43] is not possible because of the difference in heat cycles regime (higher heating temperature (65 °C), longer heating duration in each cycle (7 hours) and the application of two cycles per day in the current investigation). In addition, it is not clear whether the presence of coarse aggregates would aggravate or alleviate the loss in UPV due to heat cycles since this would depend on the relative thermal expansion coefficients of the aggregates used and mortar.

Drying Shrinkage

The shrinkage results for the tested mortars in the current investigation are shown in Figures 11 and 12, for the SF and GGBS mortars, respectively. It can be seen that the OPC mortar started to shrink as soon as it was placed in cyclic heating. However, with the SF and GGBS mortars some initial swelling occurred and then shrinkage started in all mortars except the 70 % slag one in which swelling continued throughout the heat cycles. It can be argued that the initial swelling may be due to expansion of air and water in the pores of the pozzolanic mortars as a result of heating [45]. Mortars with pozzolznic materials which inherently have a higher evaporable water content (see moisture loss section above), would be more susceptible to early swelling compared to the OPC mortar. As heating continues internal stresses are created, and the tensile strength of the mortar is exceeded leading to microcracking. After that the rate of water evaporation accelerates and shrinkage of the paste starts.

It can be seen that there was some reduction in the observed shrinkage after 56 days in cyclic heating (i.e. some minor swelling during the mainly shrinkage episode). A similar behaviour was observed by Alsayed and Amjad [18] with exposure to hot weather in Riyadh for one year. No explanation was given for this observation. The authors of the current investigation believe that the minor swelling may be due to expansion followed by cracking of inner layers of the heated mortar prisms. Subsequently, moisture migration took place from inner to outer layers, which became completely dehydrated by heating during the first 56 days. The mortars started to shrink again when the moisture, which migrated from the inner to outer layers, began to evaporate from the prisms.

The maximum observed shrinkage was at 56 days after exposure to heat cycles. On that day, the use of pozzolanic materials increased the shrinkage due to heat cycles by 120, 300, 320 and 480% for the 5, 10, 15 and 20% SF mortars, respectively, compared to the OPC mortar. The percentage increase was 280 and 600% for the 30 and 50 GGBS mortars, respectively. The continued swelling of the 70% slag mortar may be due to severe cracking (it lost more than 25% of its UPV), leading expansion by heating.

In simulated hot weather shrinkage tests carried out in the laboratory by Kharchi and Chabbi [21] the concrete shrinkage reached 1600 microstrain. Whereas, tests conducted in accordance with ASTM C 157, at the Housing and Building Research Centre in Egypt using an Egyptian SF, showed that the shrinkage of SF concrete reached 1500 microstrain at 56 days [46]. In the current investigation, the strain of the 50% GGBS mortar reached 3500 microstrain. However, in outdoor exposure tests in hot climates, the observed concrete shrinkage was less (up to 600 microstrain in most cases and not exceeding 1000 microstrain). This may be due to moisture absorption by the small sized test samples from humidity or rain during outdoor exposure. That was not discussed by the researchers who conducted the these tests, but it would explain the difference in the observed shrinkage between the laboratory and outdoor exposure results. The long term shrinkage of actual structural members need to be monitored in order to understand the effect of moisture absorption from the atmosphere on their ultimate drying shrinkage.

The shrinkage values reported herein are for mortar samples. It is accepted that mortar shrinks more than concrete due to the restraining effect of the aggregates. For example, the ultimate drying shrinkage of a 1:3 mortar is twice that of concrete [47]. Most specifications allow for drying shrinkage in the range of 600-800 microstrain at 56 days[48]. Unfortunately, different standards have different test procedures, test conditions and acceptance limits for drying shrinkage. The most stringent specification is that of the Hong Kong Housing Authority in which a 25 x 25 x 285 mm mortar prism is kept in 27 °C and 55% RH after casting. The drying shrinkage of that prism should not exceed 300 microstrain at 7 days [49]. In the current investigation a higher exposure temperature was used to simulate the conditions in the Middle East, but the mortar prism had a larger cross section and was exposed to the heat cycles for 90 days. In any case, the shrinkage values exhibited by some mortars in the current investigation may be considered excessive. It can be argued that, there is a need to devise a shrinkage test suited for the conditions in the region and set acceptance limits for drying shrinkage in accordance with that test.

SUMMARY AND CONCLUSIONS

In this investigation, mortars having water to cementitious materials ratio of 0.5 and cementitious materials to sand ratio of 1:2 without pozzolanic materials or with replacing 5, 10, 15 or 20% of the cement by silica fume or with replacing 30, 50 or 70% of the cement by ground granulated blast furnace slag, were prepared. The mortar samples were subjected to heat cycles between room temperature for 5 hours and 65 °C for 7 hours to study the effect of temperature variations during summer in the Middle East on the mortar samples. Two heat cycles were carried out every day to accelerate the deterioration. The effect of the variation in relative humidity and wind speed was not taken into account. Based on the tests carried out in this investigation, the following conclusions can be drawn:

[1] At the end of the heat cycles the percentage moisture loss was 7.3 % for OPC mortar or 9.2, 9.7, 10.7 and 11.1 for the 5, 10, 15 and 20% silica fume mortars, respectively, and 11.1, 12.8 and 13.7 % for the 30, 50 and 70% GGBS mortars, respectively.

[2] The increased moisture loss from the SF mortars is believed to be due to their increased evaporable water content since the SF reaction products

contain less water than cement hydration products. The continued moisture loss from the silica fume mortars after more than 28 days in the heat cycles is probably due to the dissolution of some cement hydration products, which tend to become unstable with a lower $Ca(OH)_2$ concentration in the pores at an advanced stage of pozzolanic reactions.

[3] The increased moisture loss from the ground granulated blast furnace slag mortars is probably due to their low rate of pozzolanic reaction, leading to increased porosity and permeability for the mixes of the current investigation.

[4] The utilization of 5, 10 or 20% silica fume in mortars kept at room temperature reduced the compressive strength. This was probably due to the fact that no superplasticisers were used in preparation of the mortars in the current investigation. The mortar with 15% silica fume exhibited an increase of 8.7% in its compressive strength. This is probably due to the consumption of most of the $Ca(OH)_2$ at this replacement level.

[5] The ordinary Portland cement mortar exhibited a reduction of 3.9% in its compressive strength after exposure to the heat cycles. The reduction for the 15 and 20 % silica fume mortars was 5.4 and 14%, respectively. Whereas, the reduction in the 30, 50 and 70% ground granulated blast furnace slag mortars was 9.2, 7.6 and 2.9%, respectively. It would appear that the loss in compressive strength was lower with mortars with a more open microstructure.

[6] The 5 and 10% silica fume mortars exhibited an increase of 4.3 and 27.5% in their compressive strength after exposure to the heat cycles. As the samples were placed in the ovens in a saturated state, it is possible that the pozzolanic reactions were re-activated by the heat in the oven, leading to the observed strength increase. It is expected that such reactions started to take places soon after the samples were placed in the ovens and continued for some time in the inner parts of the samples, where moisture was available.

[7] The loss in ultrasonic pulse velocity for the 10% silica fume and 30 and 50% ground granulated blast furnace slag mortars was 5.6, 54.2 and 9.8% lower than that observed in the Ordinary Portland cement mortar, respectively. However, unlike the other mortars, the 10% silica fume mortar lost most of its pulse velocity after more than 28 days in the heat cycles. This indicates that the 10% Silica fume mortar was more heat resistant compared to the other tested mortars. The loss in ultrasonic pulse velocity was higher for higher contents of pozzolanic materials in the mortars.

[8] Exposure to heat cycles increased the shrinkage of the tested mortars considerably. The maximum observed shrinkage for the 5, 10, 15 and 20% SF mortars was 120, 300, 320 and 480% higher than the Portland cement

mortar, respectively. The corresponding increase in shrinkage was 280 and 600% for the 30 and 50 GGBS mortars, respectively. The continued swelling during the heat cycles of the 70% slag mortar may be due to its severe cracking, leading expansion by the repeated heat cycles.

[9] The shrinkage values reported for the pozzolanic mortars in the current investigation are excessive. Outdoor exposure tests in the Middle East on concretes containing pozzolanic materials did not confirm this finding. This may be due to moisture reabsorption from humidity or rain by the small sized samples during the outdoor tests. The long term shrinkage of actual structural members need to be monitored in order to understand the effect of moisture absorption from the atmosphere on their ultimate drying shrinkage.

[10] There is a need to develop a shrinkage test that takes into account the dry arid conditions in the Middle East and set appropriate limits for drying shrinkage in accordance with that test.

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Table 1 Chemical analysis of cementitious materials used

Component	**OPC**	**SF**	**GGBS**
SiO_2	21.57	95.40	35.42
CaO	63.96	1.09	31.90
Al_2O_3	5.34	1.02	14.34
Fe_2O_3	3.42	0.79	2.56
MgO_2	0.77	0.46	7.45
BaO	-	-	5.65
SO_3^-	2.84	0.08	0.47
NaO_2	0.38	0.28	1.08
K_2O	0.19	0.42	0.67
S	-	-	0.27
Cl^-	-	-	0.06
L.O.I.	1.34	1.32	0.13

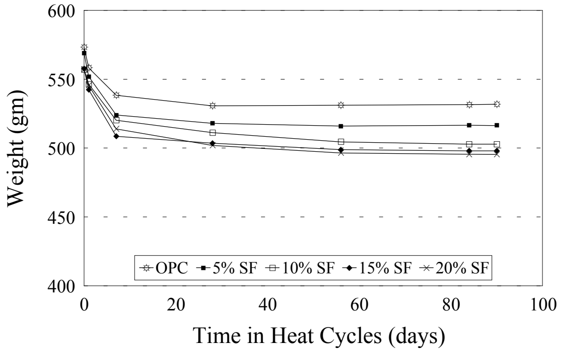

Figure1 Weight change of SF mortars due to heating

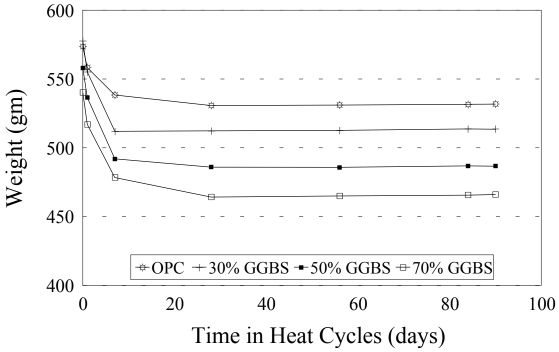

Figure 2 Weight change of GGBS mortars due to heating

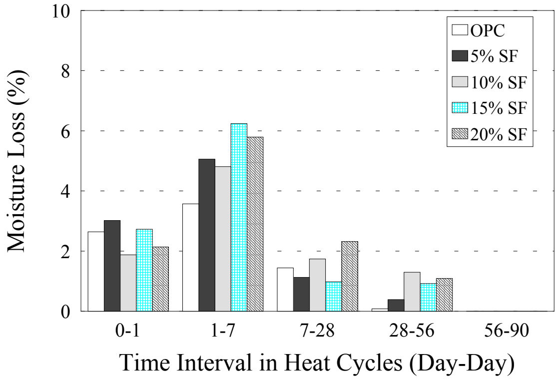

Figure 3 Moisture loss (%) at different time intervals in the heat cycles for the SF mortars

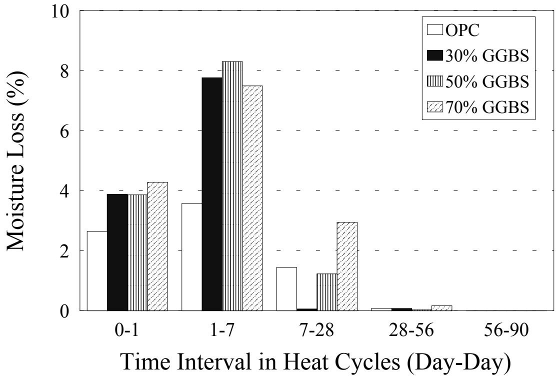

Figure 4 Moisture loss (%) at different time intervals in the heat cycles for the GGBS mortars

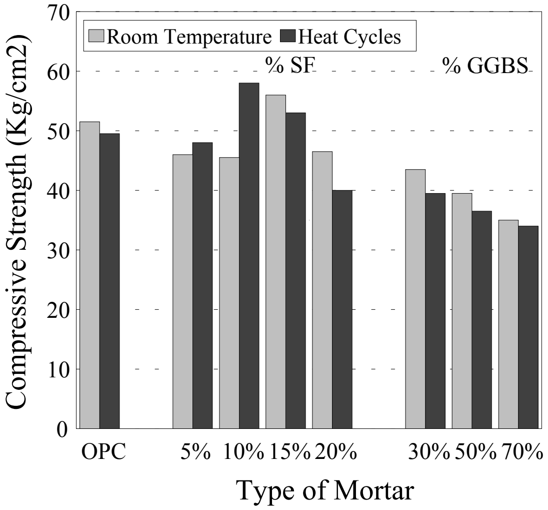

Figure 5 Compressive strength of SF and GGBS mortars subjected to different conditions

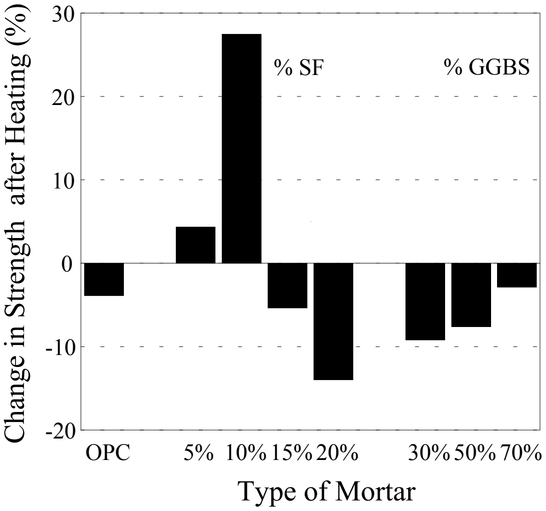

Figure 6 Percentage change in compressive strength as a result of the heat cycles

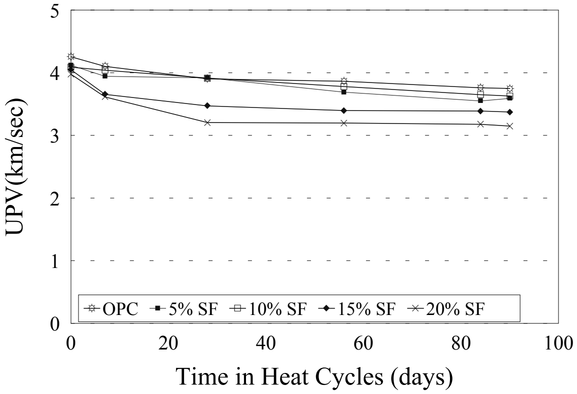

Figure 7 Effect of heat cycles on UPV of SF mortars.

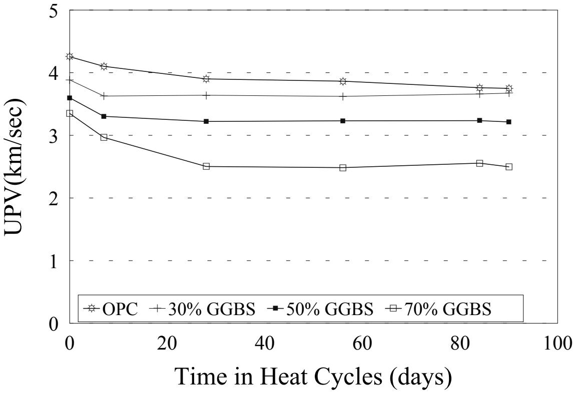

Figure 8 Effect of heat cycles on UPV of GGBS mortars.

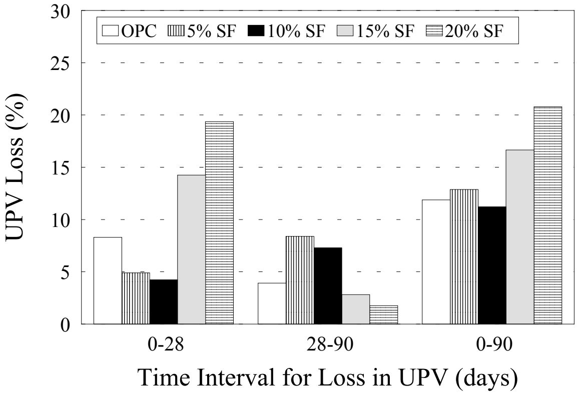

Figure 9 Loss of UPV with heat cycles for SF mortars

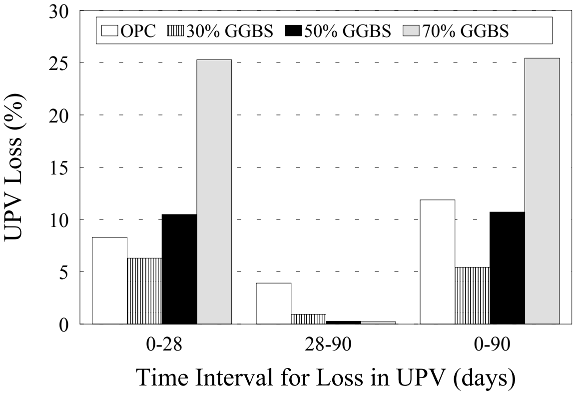

Figure 10 Loss of UPV with heat cycles for GGBS mortars

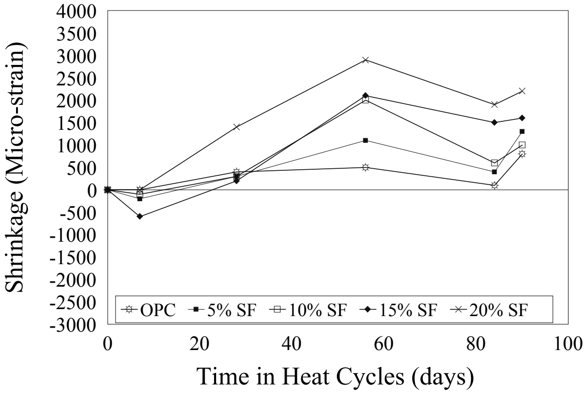

Figure 11 Length change of heat cycled SF mortars

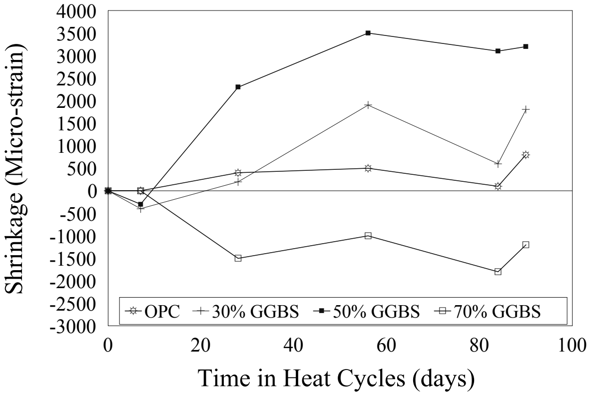

Figure 12 Length change of heat cycled GGBS mortars