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LONG -TERM MECHANICAL PROPERTIES OF HIGH STRENGTH SILICA FUME MORTAR USING ACCELERATED AGEING

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ABSTRACT

This paper presents the experimental results of the long-term mechanical properties of silica fume high strength mortar (SFHSM). Nine mixes were carried out in this study; one mix without S.F used as a reference, four mixes with S.F used as a partial replacement and four mixes with S.F used as an addition. The S.F percentage ratios used were 5, 10, 15, and 20 % of the cement weight. In all mixes the water/cementitious materials ratio was kept constant at 0.40 and the sand : cementations materials ratio was 3:1. The long-term properties were obtained by using the accelerated ageing procedure. The accelerated long-term specimens were cured in 100% relative humidity at room temperature for 28 days then in 60oC hot water till tested at 10, 30, 50, 70, 100, and 120 days. This regime was used earlier in the literature on Glass fiber reinforced concrete (GRC) and it was found that it was equivalent to 1, 3, 5, 7, 10, and 12 years, respectively, of its exposure to natural weathering in Egypt. The experimental results showed a slight gradual increase in the compressive strength, indirect tensile strength, and flexural strength of SFHSM on the long-term as compared to the short-term results followed by a small reduction in the strengths after a certain age. S.F mortar specimens having 10% S.F as a partial replacement of cement weight showed about 9, 22, 16 % increases in the compressive, indirect-tensile, and flexural strengths, respectively, of those of 56 days strengths after 70 days immersion in hot water, followed by a small reduction of about 8, 6, and 5 % in the compressive, indirect-tensile, and flexural strengths, respectively, at 120 days in hot water.

يهدف هذا البحث لدراسة الخواص الميكانيكية للمونة عالية المقاومة المحتوية على غبار السيليكا على المدى البعيد. اشتملت الدراسة على تسعة خلطات: خلطة بدون غبار السيليكا و هي الخلطة المرجعية و أربعة خلطات محتوية على غبار السيليكا كإحلال جزئي من محتوى الأسمنت و أربعة خلطات محتوية على غبار السيليكا كإضافة إلى محتوى الأسمنت. و كانت نسب غبار السيليكا المستخدمة ٥، ١٠، ١٥، ٢٠ % من وزن الأسمنت. و في كل الخلطات كانت نسبة الماء إلى المواد الأسمنتية ٤, ٠ و نسبة الرمل إلى المواد الأسمنتية ٣:١ . و قد تم استخدام تقنية الاختبارات المعجلة لدراسة الخواص على المدى البعيد حيث تم معالجة العينات عند درجة رطوبة ١٠٠ % لمدة ٢٨ يوما ثم تعريضها لماء درجة حرارته ٦٠ ° مئوية حتى اختبارها بعد ١٠، ٣٠، ٥٠، ٧٠، ١٠٠، ١٢٠ يوما. و قد استخدم هذا الاختبار من قبل على الخرسانة المسلحة بالألياف الزجاجية و وجد أن برنامج المعالجة المذكور يكافئ تعريض تلك العينات إلى المناخ الطبيعي في مصر لمدة ١، ٣، ٥، ٧، ١٠، ١٢ سنة على التوالي. أظهرت النتائج المعملية زيادة تدريجية طفيفة في مقاومة الضغط و الشد الغير مباشر و الانحناء على المدى البعيد متبوعة بنقص صغير في المقاومة بعد فترة معينة. و على سبيل المثال فقد أظهرت عينات المونة المحتوية على ١٠ % غبار السيليكا كإحلال جزئي من محتوى الأسمنت زيادة في مقاومة الضغط و الشد الغير مباشر و الانحناء بحوالي ٩، ٢٢، ١٦ % على التوالي بعد ٧٠ يوما من الغمر في الماء الساخن بالمقارنة بمقاومتها بعد ٦٥ يوما من المعالجة التقليدية و تبع ذلك نقص صغير بحوالي ٨، ٦، ٥ % في مقاومة الضغط و الشد الغير مباشر و الانحناء على التوالي بعد ١٢٠ يوما من الغمر في الماء الساخن.

Keywords: Mortar specimens; silica fume; mechanical properties; long term; accelerated ageing

1. INTRODUCTION

Silica fume concrete (SFC) is a relatively new material which has achieved widespread use in the construction industry. Use of a new civil engineering material requires one to know its long-term behavior, or failing this, to have a reliable way of predicting it, at least for the anticipated life of the structure. The long - term strength may be obtained from exposure test samples to real working conditions over the expected working lifetimes, or estimated from the behavior of samples exposed to much more aggressive accelerated ageing conditions over shorter time periods.

Under real working conditions Gjørv [1] tested Ordinary Portland cement concrete (OPCC) specimens immersed in seawater for about 30 years in Trondhiem, Norway, he reported that, in general, compressive and flexural strengths in concrete made with OPC showed strength retrogressions after about 5 years of immersion. Also 50 years properties of OPCC were tested by Washa et. al. [2], the authors found that the compressive strength of concrete cylinders generally increased as the logarithm of the age increased for about 10 years. After 10 years the compressive strength decreased or remained essentially the same, the modulus of rupture was approximately one-tenth of the compressive strength.

For silica fume high strength concrete (SFHSC) Carette [3] found significant strength loss in the compressive strength up to more that 20% between 3 months and 2 years in SFC cured in air while comparable concrete without S.F cured under the same conditions showed continued strength gain. Kurdi and Koury [4] tested two groups of mixes; the first group was silica fume normal strength concrete (SFNSC), which contained a control mix (without S.F) and five mixes with 5, 10, 15, 20, and 25 % S.F with W/(C+S.F) of 0.60. The second group was SFHSC, which contained a control mix and five mixes with 5, 10, 15, 20, and 25 % S.F and W/(C+S.F) of 0.35. The results showed a non negligible drop in strengths of all OPCC and SFHSC between the ages of 180 days and 3 years; except for concretes containing 5% S.F normal strength and high strength concretes.

The long-term effects (3 years) of S.F, at concentrations up to 25% of the cement weight were studied on the compressive and flexural strengths of concretes cured in water and in air. The W/C ratio was varied between 0.38 and 1.32. The compressive strength of concrete cured in water showed a continuous increase with age, while slight differences – positive or negative – were observed between 1 year and 3 years in compressive and flexural strengths of concrete cured in air [5]. Sasatani et. al. [6] studied SFHSC compressive strength among other concrete mixes in four different environments for five years. The four environments were as follows: A- in water at 20°C (wet condition), B- in air at 20°C and 60% RH (dry condition indoor), C- on the roof of a building in Kanazawa University (repeated wet and dry conditions, outdoor), and D- on the tidal zone at Matsuto beach facing the sea of Japan (repeated wet and dry conditions, marine environment). They found that 10% S.F concrete showed some reduction in compressive strength with exposure time when they were initially cured in water for 7 days and then continuously air-cured indoor for a long period. On the other hand the long-term behavior of SFC was studied for 10 years using cubes 100×100×100 mm dimensions. The test specimens were cured in water at 20°C or in air at 20°C and 50 % RH. It was specified that the same procedures and the same apparatus were used for all tests. The compressive strength of the specimens cured in water increased continually with time, together with that of most of the specimens cured in air. The gains of strength observed were however less than in the case of curing in water. In the case of some SFC cured in air, a slight loss of compressive strength was deserved at 3 years, which disappeared at 10 years [5]. Aitcin and Laplante [7] indicated no tendency for long-term (4-6 years) strength loss in SFC. Also, Lachemi et al. [8] tested a sidewalk at Skw Canada. After 16 years they found that the concrete containing S.F have shown a better long-term behavior than the plain concrete without S.F that was used to construct a small part of the sidewalk. El-Aiat et. al. [9] tested HSC specimens at ages of 28, 360, 540 and 720 days. The S.F was used as an addition of 10% by weight of cement. The test results showed that the compressive, tensile and flexural strengths generally increase, with higher early age strength and higher early rate of strength gain, with time up to about two years.

Judgment on the adequacy of concrete is needed on the construction site much sooner than 28 days or even 7 days. There have been many attempts for the meaningful early determination of the strength potential of concrete [10]. The use of external heat sources for accelerated determination of control strengths began more than 60 years ago. Since then a wide variety of accelerated test methods have been recommended by various investigators. The highest temperature to be applied is usually that of a boiling water bath. When lower temperatures are used, the curing ambience is water or steam, although dry hot air has also been used with sealed molds [11]. Sabir [12] studied the influence of S.F on the strength development of concrete with S.F content in the range of 12-28%. Results were given for compressive strengths up to 91 days for two water curing temperatures 20°C and 50°C. He found that at higher temperatures of curing (50°C) a higher compressive strength was obtained at early ages, but this trend was reversed with increasing age. For high-strength concrete when cured at 20°C it was shown that up to 16% S.F the reduction caused by the higher temperature was of the order of 4-10%. Beyond 16% S.F content, however, the higher temperature caused an increase in the 28-day compressive strength of about 8-17%. Curing at temperatures below 20°C retarded strength development more in case of SFC than in case of control concrete. S.F makes it possible to design low-heat concrete over a wide range of strength levels. Therefore, S.F is more sensitive to curing temperature than OPC [13]. But on the other hand, Yamoto et. al. [14] reported that when concrete was cured at 10°C, the presence of silica fume did not essentially improve the strength of concrete at 7 days; however, it did at both 28 and 91 days. With higher curing temperature of 20, 30 and 65°C, the presence of silica fume substantially improved the 7-

day strength, as well as strengths after longer curing periods.

The accelerated ageing method is based on an assumption that measuring mechanical properties after storing specimens in water at elevated temperatures for short times may serve for predicting the mechanical properties of the material after long time of natural weathering. Early work at Building Research Establishment (U.K) had indicated that Glass fiber reinforced concrete (GRC) composites lost strength more rapidly when immersed in hot water. Litherland et. al. [15] tested GRC and the results of tests on the composites stored in artificial accelerated ageing conditions showed a consistent pattern of falling strength followed by a stable strength region. Composite strength changes in a variety of real climates showed similar patterns of behavior in initial falling strength region, with the same activation energy and a temperature dependence as the accelerated tests. Good correspondence was observed between predicted behavior and actual weathering over 10 years in the UK; a correlation of data under accelerated ageing and under natural weathering was obtained. Such Correlation has been made for the UK climate in which 1 day of storage in water at 60oC was equivalent to 272 days of natural weathering. Aindow et. al. [16] recently, however, showed that additional results have become available from materials exposed over a number of years in warmer climates, where changes occur significantly more quickly. For the purposes of comparison, the data from these hot sites has been treated as if it were accelerated ageing data in relation to the cooler UK climate. It has been transposed to the appropriate age in the UK weather using the acceleration factors given in Table (1), which were calculated from the mean annual temperature of the site. Based on the above discussion, and on the information obtained from the Egyptian Meteorological Authority (Cairo Airport Meteorological station) that the mean annual temperature in Cairo is about 26.5oC the acceleration factor of Egypt related to the UK is around 7.5. Hence, it could be said for GRC that one day of storage in water at 60oC is equivalent to 36.5 days of natural weathering in Egypt [17].

In this research work, the mechanical properties of SFHSM on the short-term and the optimum ratio of S.F content were studied and presented in an earlier work [18,19]. Here, the experimental results of the accelerated long-term mechanical properties of SFHSM are presented and discussed. The long-term specimens were cured in 100% relative humidity at room temperature for 28 days then in 60oC hot water till tested at 10, 30, 50, 70, 100, and 120 days. This regime used earlier in the literature on GRC was found to be equivalent to 1, 3, 5, 7, 10, and 12 years, respectively, of its exposure to natural weathering in Egypt [15, 16, 17]. Compressive, indirect tensile, and flexural strength tests were performed on the cubic, cylindrical, and prismatic long - term specimens, respectively.

2. EXPERIMENTAL INVESTIGATION

Ordinary Portland cement (OPC) produced by the Suez company and meeting the requirements of ESS 373/1991 was used. Its fineness in terms of specific surface area was 3120 cm^2/gm and its initial and final setting times were 100 minutes and 5.0 hours, respectively. Natural siliceous sand was used with a fineness modulus of 2.7, bulk density of 1.67 ton/m^3, and specific gravity of 2.55. Clean tap water without special taste, smell, color or turbidity was used. The silica fume was brought from factories of the Egyptian ferroalloys company located in Edfou, Egypt, with light gray color, specific surface area of $15.2x10^4$ cm^2/gm, bulk density of 355 kg/m^3, and specific gravity of 2.15. To keep the slump constant for all mixes; the high range water reducer (HRWR), Addicrete BVF1, was used.

The work reported here involves one reference mix without silica fume and eight mixes with silica fume (Table2). The silica fume was used as a partial replacement and as an addition to the cement content; its percentages were 5, 10, 15 and 20 % of the cement weight. The sand to cementitious materials (OPC+S.F) ratio was kept constant at 3:1 by weight. The water to cementitious materials (W/OPC+S.F) ratio was kept constant at 0.40 and HRWR dose was determined to obtain a constant slump flow of mortar of about 125 mm diameter.

Mixing was performed using a small rotary drum mixer with high efficiency. The mixing procedure consisted of mixing all dry materials till obtaining a homogeneous mix (about 90 seconds) and then half of gauging water was added gradually while the mixer was rotating and the mortar was mixed for 3 minutes. The admixture (Addicrete BVF1) was then added to the remaining water (1/2 of the gauging water) and introduced over 30 seconds and the mortar was mixed for another 3 minutes to insure full mixing.

Three types of specimens were made: 50 mm cubes, 75x150 mm cylinders and 50x50x250 mm prismatic beams. At least three specimens were prepared to be tested at each testing condition in order to get their average value.

After casting, the specimens were stored in the laboratory at room temperature for 24 hours, and then they were removed from the molds. The specimens were cured in 100% relative humidity at room temperature for 28 days then in 60^oC hot water till tested at 10, 30, 50, 70, 100 and 120 days. For the purpose of accelerated ageing, a special curing tank was made. The tank dimensions were 100x100x80 cm with a heater of 2000 Watt power. The heater was fixed in the tank bottom center to allow good distribution of heat. The tank body was made of galvanized mild steel, and its boundaries were isolated with glass wool. The tank was put in a wooden box with a top cover, and a thermostat was used to control the water heat in the tank at the required temperature.

Finally, compressive, indirect tensile, and flexural strength tests were performed on the cubic, cylindrical, and prismatic long - term specimens, respectively

3. RESULTS AND DISCUSSION

3.1 Compressive Strength

Replacement case: Table (3) and Fig. (1-a) show the average results of the compressive strength test of plain mortar specimens and specimens containing S.F with percentage ratios of 5, 10, 15 and 20 as a partial replacement of the cement weight (N, R5, R10, R15, and R20, respectively). Results of the compressive strength were calculated in N/mm^2 and as a percentage of the corresponding reference mix result. The age of the test specimens was given in terms of the duration of immersion of the test specimens in hot water at 60^{o}C. The first point in each curve in the figure represents the short-term compressive strength and represented by the value of the compressive strength of the test specimens of the respective mix at 56 days for comparison purposes.

It can be seen that plain mortar specimens showed a slight gradual increase in the compressive strength on the accelerated long-term condition as compared to the short-term compressive strength at 56 days. This slight increase reached about 15 % of that of the 56 days strength after 100 days immersion in hot water at 60^{o}C, after which a smaller reduction in compressive strength occurred of about 5% of that of the 56 days strength at 120 days of immersion in hot water.

With regard to the performance of SFHSM specimens, a similar trend of results to that of the plain mortar specimens was obtained; only a slight gradual increase in the compressive strength was obtained when compared to the 56 days strength of the respective S.F mix up to a certain duration period in the hot water, after which a slight reduction in the strength occurred. For example, the mix of 5% S.F partial replacement (R5) showed an increase in the compressive strength of about 5% of that of the 56 days strength after 70 days of immersion in the hot water; after which a smaller reduction in the compressive strength occurred of about 4% of that of the 56 days strength at 120 days of immersion in the hot water.

The corresponding values for the mix of 15% S.F partial replacement (R15) were about 15% increase in the compressive strength of that of the 56 days strength after 70 days of immersion in the hot water; followed by a reduction in the strength of about 3% at 120 days of immersion in the hot water. The reduction in the compressive strength of the accelerated ageing specimens may be related to the carbonation effect: the decrease of the strength of mortar specimens after a long time may be due to the effect of carbon dioxide (CO_2) on the hydrated products of cement. The CO_2 can decompose calcium silicate hydrate (C-S-H). This gives calcium carbonate ($CaCO_3$), which has a low strength in comparison with the C-S-H products; and silica gel which has swelling properties and no binding characteristics, thus, the strength of mortar decreases. Also, the CO_2 can react with the calcium hydroxide ($Ca(OH)_2$) librated from the hydration of the Portland cement. Another possible reason for such reduction in the strength after a long time may be due to the following: it has also become apparent that micro-silica is typically incompletely dispersed, so that the formation of agglomerates causes the mean particle size to be in the range 1-50 µm, rather than the 0.1 - 0.2 µm range frequently cited [20]. Exceptionally course agglomerations of micro-silica have the potential to behave as alkali-silica reactive aggregate particles and examples of resultant damage to concrete have been reported [21].

However the gain of strength due to the presence of S.F, which was obtained in the short-term interval, was also reflected in the results of the accelerated long-term interval.

Addition case: Table (3) and Fig. (1-b) show the average results of compressive test on the accelerated long-term condition of plain mortar specimens and specimens containing S.F with percentage ratios of 5, 10, 15, and 20 as an addition to cement content (A5, A10, A15, and A20, respectively). Results of the compressive strength were calculated in N/mm^2 and as a percentage of the corresponding reference mix result. It can be seen clearly that the results here for the addition case are similar to those of the replacement case showing a slight gradual increase in the compressive strength on the accelerated long-term condition as compared to the short-term strength followed by a smaller reduction in the strength after a certain age.

As a comparison between the results of compressive strength of specimens containing S.F as a replacement and as an addition of cement weight; First and on the short-term at 56 days [21], it can be noted that the compressive strengths of specimens containing S.F as a replacement were little higher than the compressive strength of specimens containing S.F as an addition at the same ratios. For the first while one can expect that specimens containing S.F as an addition would give compressive strength results higher than specimens containing the same ratios of S.F as a replacement in contrast to the results obtained here. However, the results obtained can be explained as follows: mixes containing S.F as an addition had the same water/cementitious ratio and also the same sand/cementitious ratio as the control mix and mixes containing S.F as a replacement, which means that in these mixes small amounts of water and sand were also added to keep these ratios the same (Table2). This means that comparing between a mix with 10 % S.F as an addition, for example, and a mix with 10 % S.F as a replacement shows that the first one had an increase in the amounts of all its ingredients except S.F when compared to the second mix, which means that the first had a smaller S.F/C ratio than the other, and as a result, it would be expected to have a lower strength than that of the second mix and this was the result obtained (Table 3 and Fig. 1).

Second and on the long-term, it can be noted that the results of the mixes of the same percentage of S.F content as replacement or addition were close to each other and having the same trend of results on the accelerated long-term. This confirms the behavior of the SFHSM mixes on the accelerated long-term deduced from the test results, for example see Fig. (2).

It is worth here at the end of this portion of analysis of results on the accelerated long-term behavior of SFHSM specimens under compression to mention that high strength concrete is usually designed for the 56 days compressive strength and the additional strength gained with time on the long-term run as a result of the continuation of the chemical reaction at a quite lower rate of reaction is considered as a margin of safety.

3.2 Indirect Tensile Strength

Replacement case: Table (4) and Fig. (3-a) show the average results of the indirect tensile strength test of plain mortar specimens and specimens containing S.F with percentage ratios of 5, 10, 15 and 20 as a partial replacement of cement weight (N, R5, R10, R15, and R20). As shown the plain mortar specimens showed a little gradual increase in the indirect tensile (splitting) strength with time on the accelerated long-term interval as compared to the short-term indirect tensile strength at 56 days. This increase reached about 21% of that of the 56 days strength after 100 days of curing in hot water. But at 120 days of curing, the indirect tensile strength decreased by about 14% of that of the 56 days indirect tensile strength.

Also, the SFHSM specimens on the accelerated long-term showed a similar trend of results to that of the plain mortar specimens; a little gradual increase in the indirect tensile strength was recorded when compared to the 56 days indirect tensile strength of the respective S.F mix up to a certain age in hot water, then a little reduction in strength was occurred. For example, the mix of 5% S.F partial replacement (R5) showed an increase in the indirect tensile strength of about 18% of that of the 56 days strength after 100 days of curing in hot water, after which the indirect tensile strength remained nearly constant up to 120 days of curing in hot water. Also, in the case of the mix of 15% S.F partial replacement (R15) there was an increase in the indirect-tensile strength after 100 days in hot water for curing of about 28% of that of the 56 days strength, after which the indirect tensile strength remained nearly constant up to 120 days of curing in hot water.

Addition case: Table (4) and Fig. (3-b) show the average results of the indirect tensile test on the accelerated long-term of plain mortar specimens and specimens containing S.F as an addition to the cement content with percentage ratios 5, 10, 15 and 20 from the cement weight.

The gain of strength due to the presence of S.F, which was obtained in the short-term interval, was also reflected in the results of the accelerated long-term interval. For example, the mix of 5% S.F addition (A5) showed an increase in the indirect tensile strength of about 20% of the 56 days strength after 50 days of curing. But after 120 days of curing a 9 % reduction in the indirect tensile strength occurred. Also, for the 15% S.F addition mix (A15), an increase occurred in the indirect tensile strength of about 28% of the 56 days strength after 100 days of curing in hot water. But after 120 days of curing in hot water a 17% reduction in the indirect tensile strength occurred.

As a comparison between the results of the indirect tensile strength of specimens containing S.F with ratios 5, 10, 15 and 20 % as replacement and addition cases, It can be seen from Table (4) that the indirect tensile strength of mixes of the same percentages of S.F content were so close to each other and having the same trend of results on the long-term (Fig. 5). This confirms the behavior of SFHSM on the long-term deduced from the test results.

It is worth here at the end of this portion of analysis of results on the accelerated long-term behavior of SFHSM specimens to mention that results of the indirect tensile strength were having the same trend of results as those of the compressive test specimens.

3.3 Flexural Strength

Replacement case: The average results of the flexural strength test of plain mortar specimens and specimens containing S.F with partial replacement ratios of 5, 10, 15 and 20% (R5, R10, R15 and R20, respectively) by cement weight are shown in Table (5) and Fig. (5-a). It can be seen that the plain mortar specimens showed a gradual increase in the flexural strength with time on the accelerated long-term interval compared to the short-term flexural strength at 56 days. This increase was about 23% of that of the 56 days short-term strength after 70 days of curing in 60^oC hot water. But after 120 days of hot water curing about 17 % reduction in the flexural strength occurred. Also, SFHSM specimens on the accelerated long-term followed the same trend of results of the plain mortar specimens; the flexural strength gradually increased with time on the long-term interval with respect to the 56 days flexural strength of the respective S.F mix till a certain age in hot water. For example, the mix of 5% S.F partial replacement (R5) of cement weight showed an increase in the flexural strength of about 27% of that of the 56 days strength after 70 days in hot water. But after 120 days of hot water curing about 2% reduction in the flexural strength occurred. Also the mix of 15% S.F partial replacement (R15) of cement weight showed an increase in the flexural strength of about 7% of that of 56 days short-term flexural strength after 50 days in hot water. But after 120 days in hot water about 16% reduction occurred. However, some of the mixes showed a reduction in the flexural strength after a certain age in hot water slightly less than the 56 day strength as shown in Table (5) and Fig. (5-a). The compression and indirect tension tests for those mixes did not show results on the accelerated long-term less than the 56 days strength. This contradiction could be cited in some results in the literature [21]. However another group of the tested mixes showed the same trend of results of the flexural strength as those of the compressive and indirect tensile strengths.

Therefore, the relatively higher reduction in the flexural strength on the accelerated long-term in comparison to the behavior under compression and splitting tension needs further investigation in future studies.

Addition case: Table (5) and Fig. (5-b) show the average flexural strength test results of plain mortar specimens and specimens containing 5, 10, 15 and 20% S.F addition ratios by cement weight (A5, A10, A15 and A20, respectively). The results showed that the flexural strength values of specimens contained S.F as an addition was improved with time on the accelerated long-term interval up to a certain age and then decreased. For example, at 5% S.F addition ratio (A5), there was an increase in the flexural strength of about 3% of that of 56 days short-term flexural strength after 70 days of curing in hot water, but after 120 days of curing this increase was vanished. Also at 15% S.F addition mix (A15), there was an increase in the flexural strength of about 6% after 70 days of curing in hot water, but after 120 days of curing a reduction in the flexural strength occurred of about 15%.

Table (5) shows a comparison between the results of the flexural strength of specimens containing S.F with ratios 5, 10, 15 and 20 % as replacement and addition cases. However, it should be noted that the comparison between the results of specimens containing S.F as a replacement and those containing S.F as an addition was more clear in the case of the compressive and indirect splitting tensile strength than in the case of flexural strength, and this can be related to the nature of these tests and the accuracy obtained in each of them, see Fig. (6).

4. CONCLUSIONS

1- Plain mortar specimens showed slight gradual increase in the compressive, indirect tensile and flexural strengths on the long-term as compared to the short-term results followed by a small reduction in the strengths after a certain age.

2- Plain mortar specimens showed about 14%, 15, and 23 % increases in the compressive strength, indirect-tensile, and flexural strengths, respectively, after 70 days of immersion in hot water at 60 oC as compared to the corresponding 56 days strengths, and followed by a reduction of about 3, 8, and 17 % in the compressive strength, indirect-tensile, and flexural strengths, respectively, after120 days of immersion in hot water.

3- Silica fume high strength mortar specimens showed the same trend on the accelerated long-term behavior as that of plain mortar specimens under compression, indirect tension and flexure tests.

4- S.F mortar specimens having 10% S.F as a partial replacement of cement weight showed about 9, 22, 16 % increases in the compressive, indirect-tensile, and flexural strengths, respectively of those of 56 days strengths after 70 days immersion in hot water, followed by a small reduction of about 8, 6, and 5 % in the compressive, indirect-tensile, and flexural strengths, respectively, at 120 days in hot water.

5- S.F mortar specimens having 15% S.F as a partial replacement of cement weight showed about 15, 22, 1 % increases in the compressive, indirect-tensile, and flexural strengths, respectively of those of 56 days strengths after 70 days immersion in hot water, followed by a small reduction of about 3, an increase of about 6%, and a reduction of about 10% in the compressive, indirect-tensile, and flexural strengths, respectively, at 120 days in hot water.

6- The reduction in strength obtained on the accelerated long-term may be due to the carbonation effect and also the tendency of some of the S.F to agglomerate and showing a potential for the alkali-silica reaction.

7- The gain in strength obtained on the accelerated long-term was considered a margin of safety as high strength concrete is usually designed for the 56 days compressive strength according to the standard codes of practice.

8- The behavior of SFHSM specimens on the accelerated long-term under flexure needs further investigation as not all the obtained results were in agreement with the trend of results of the compression and splitting tension test specimens.

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Table 1, Acceleration factors of various warm climate sites related to UK [16]

Site	**Mean annual temperature (^oC)**	**Time equivalent to UK**
United Kingdom	10.4	1
Arizona, US	21.7	4.2
Lnnisfail, Australia	23.6	5.5
Cloncurry, Australia	26.2	7.3
Lagos, Nigeria	26.7	7.8
Bombay, India	27.6	8.4

Table 2, Mix proportions of the mixes tested.

Mix Symbol	Mix type	Ingredients					% Ratios					
		Cement (C) Kg	S.F Kg	Sand (S) Kg	Water (W) Liter	SUP* gm	$\frac{S.F}{C}$	$\frac{W}{C}$	$\frac{S}{C}$	$\frac{W}{C+S.F}$	$\frac{S}{c+S.F}$	$\frac{Sup}{c+S.F}$
N	Normal mix	31.00	-----	92.90	12.40	528	0.00	40.00	300.00 315.45 332.97 351.2337 3.09315. 00330.00 345.0036 0.00	40	300	1.7
R_5	5% Rep.	29.45	1.55	92.90	12.40	600	5.26	42.10		40	300	1.9
R_{10}	10% Rep.	27.90	3.10	92.90	12.40	620	11.11	44.44		40	300	2.0
R_{15}	15% Rep.	26.45	4.65	92.90	12.40	660	17.58	46.88		40	300	2.1
R_{20}	20% Rep.	24.90	6.20	92.90	12.40	680	24.90	49.80		40	300	2.2
A_5	5% Add.	31.00	1.55	97.65	13.02	560	5.00	42.58		40	300	1.7
A_{10}	10% Add.	31.00	3.10	102.30	13.64	570	10.00	44.00		40	300	1.7
A_{15}	15% Add.	31.00	4.65	106.95	14.26	590	15.00	46.00		40	300	1.7
A_{20}	20% Add.	31.00	6.20	111.60	14.88	620	20.00	48.00		40	300	1.7

*:Superplasticizer

Table 3, Results of the compressive strength test specimens in N/mm^2 and as a percentage of the corresponding reference result at durations in days of 60 °C hot water exposure

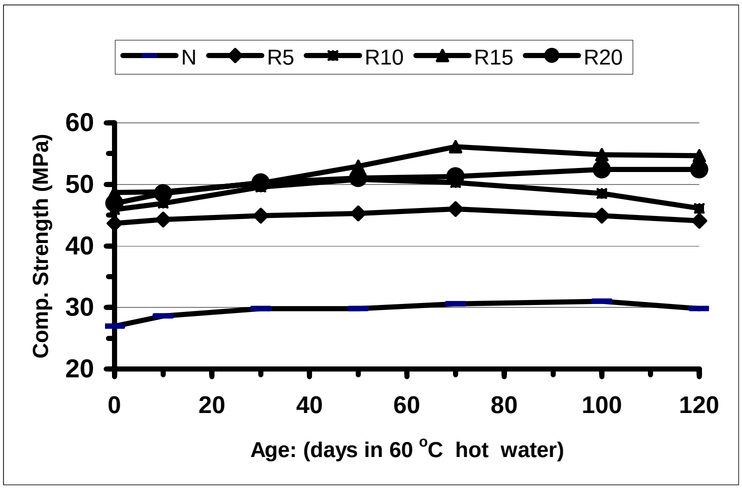
Compressive strength, N/mm^2							**% compressive strength**						
56 days strength	10 days	30 days	50 days	70 days	100 days	120 days	56 days strength	10 days	30 days	50 days	70 days	100 days	120 days
26.93	28.6	29.78	29.78	30.60	31.01	29.78	100	100	100	100	100	100	100
43.66	44.27	44.88	45.29	45.98	44.88	44.06	162	155	151	152	150	145	148
45.90	46.92	49.57	50.80	50.31	48.55	46.1	170	162	166	171	164	175	151
48.67	48.80	50.78	52.92	56.10	54.79	54.67	181	171	168	178	183	176	184
46.92	48.55	50.31	51.00	51.29	52.43	52.43	174	170	169	171	168	169	176
42.84	44.06	45.98	46.51	46.63	48.18	46.51	159	154	154	156	152	155	156
43.66	46.54	47.33	48.55	49.49	50.39	48.96	170	163	159	163	162	162	164
44.06	46.92	47.94	51.00	51.80	51.00	48.96	164	164	161	171	169	164	163
45.29	48.55	49.37	51.82	52.63	52.00	50.80	168	170	166	174	172	168	171

Table 4, Results of the Indirect tensile (splitting) strength test specimens in N/mm^2 and as a percentage of the corresponding reference result at durations in days of 60 ^{o}C hot water exposure

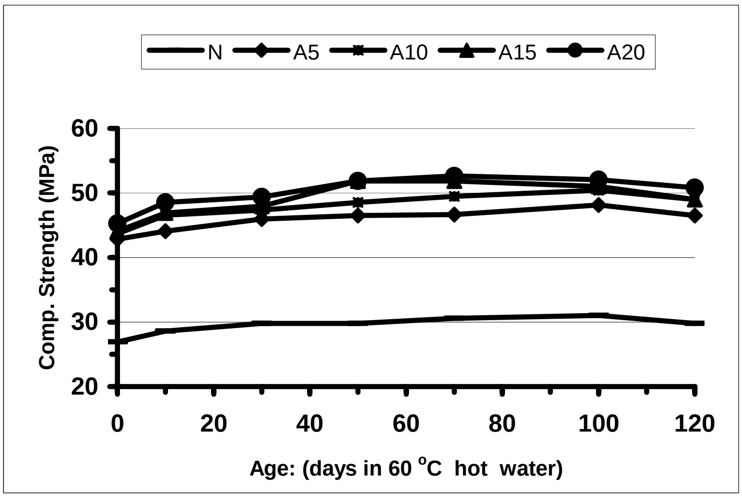
Mix symbol	**Indirect tensile (splitting) strength, N/mm^2**							**% Indirect tensile (splitting) strength**						
	56 days strength	10 days	30 days	50 days	70 days	100 days	120 days	56 days strength	10 days	30 days	50 days	70 days	100 days	120 days
N	3.5	3.66	3.83	3.92	4.02	4.23	3.75	100	100	100	100	100	100	100
R5	4.62	4.70	4.79	5.04	5.25	5.45	5.45	90	128	125	129	131	129	145
R10	4.93	5.21	5.49	5.77	6.03	6.29	5.65	141	142	143	147	150	149	151
R15	5.08	5.31	5.63	6.13	6.20	6.50	6.49	145	145	147	156	154	154	173
R20	4.78	5.01	5.23	5.71	6.06	6.55	6.29	137	137	137	146	151	155	167
A5	4.15	4.62	4.79	4.99	4.96	4.73	4.62	119	126	125	137	123	112	123
A10	4.62	4.70	4.86	5.02	5.38	5.74	5.14	132	128	127	128	134	136	137
A15	4.73	5.08	5.42	5.48	5.77	6.06	5.25	135	139	142	140	144	143	140
A20	4.83	4.96	5.31	5.44	5.41	5.91	5.34	138	136	139	139	135	140	142

Table 5, Results of the Flexural strength test specimens in N/mm^2 and as a percentage of the corresponding reference result at durations in days of 60 ^{o}C hot water exposure

Mix Symbol	**Flexural strength, N/mm^2**							**% Flexural strength**						
	56 days strength	10 days	30 days	50 days	70 days	100 days	120 days	56 days strength	10 days	30 days	50 days	70 days	100 days	120 days
N	5.75	5.75	6.85	6.85	7.1	6.61	6.12	100	100	100	100	100	100	100
R5	7.34	8.32	8.45	8.57	9.30	9.18	9.18	128	134	123	125	131	139	150
R10	8.45	8.57	9.55	10.16	9.79	9.55	9.30	148	140	139	148	138	144	152
R15	10.77	11.02	11.26	11.51	10.89	10.16	9.79	188	180	164	168	153	154	160
R20	9.42	9.42	9.55	9.79	9.30	9.18	9.18	158	154	139	143	131	139	150
A5	7.96	7.96	8.08	8.08	8.20	7.96	7.96	131	130	118	118	115	120	130
A10	10.28	10.77	11.26	11.02	10.65	9.91	9.42	179	176	164	161	150	150	154
A15	11.02	11.38	11.75	11.75	11.26	10.65	10.04	143	186	172	172	159	161	164
A20	11.02	11.26	11.51	11.51	11.02	10.28	9.79	193	184	168	168	155	156	160



(a) S.F was used as a partial replacement



(b) S.F was used as an addition

Fig. 1 The effect of S.F content on the long-term compressive strength of mortar specimens

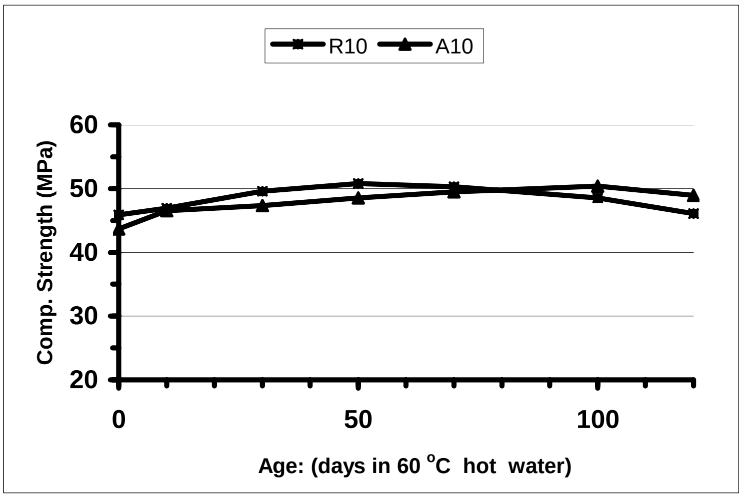
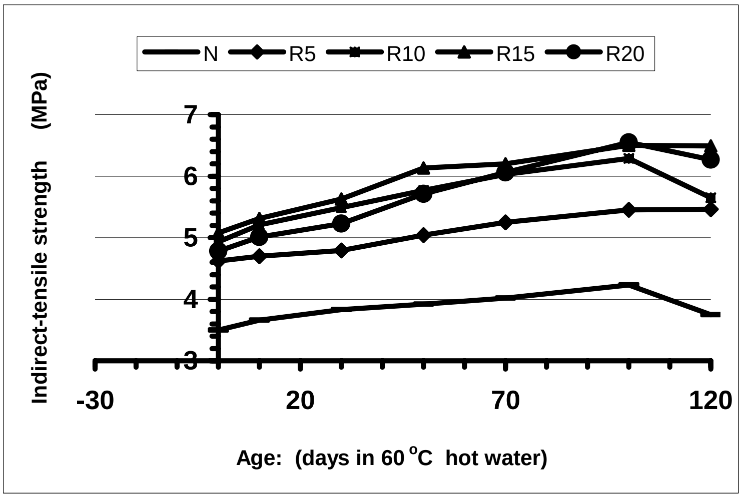
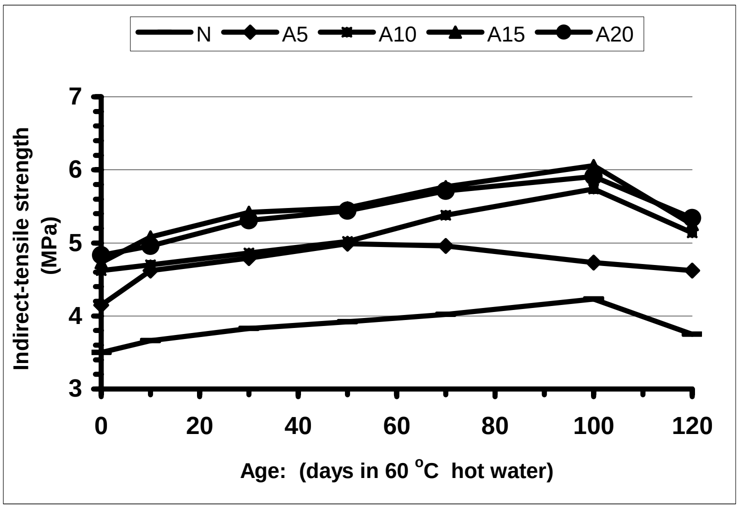


Fig. 2 Compressive strength of mortar specimens with 10% S.F as a replacement and as an addition



(a) S.F was used as a partial replacement



(b) S.F was used as an addition

Fig. 3 The effect of S.F content on the indirect tensile strength of the mortar specimens

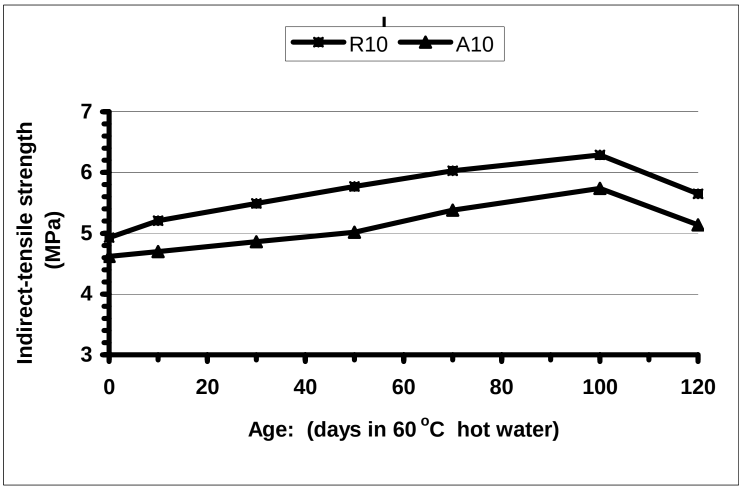
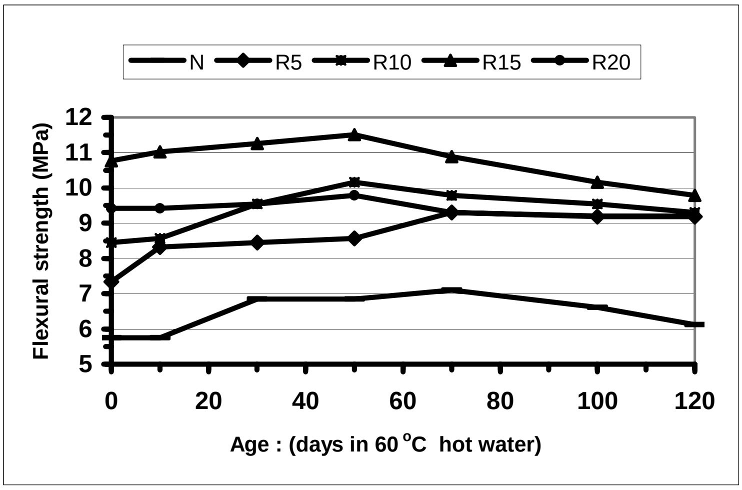
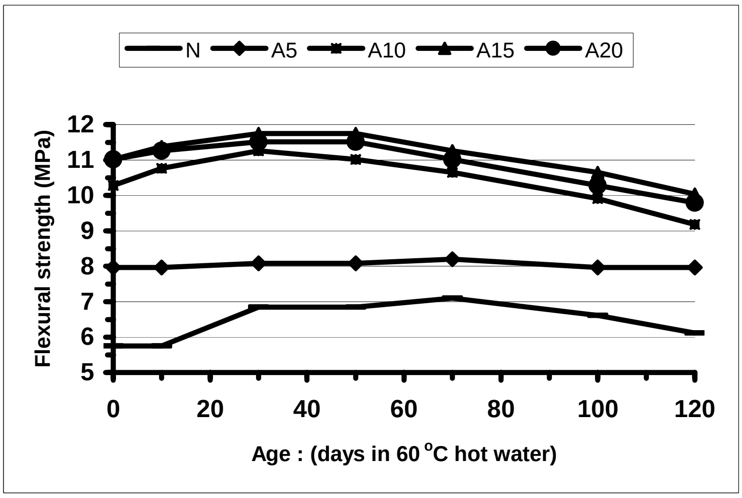


Fig. 4 Indirect tensile strength of mortar specimens with 10% S.F as a replacement and as an addition



(a) S.F was used as a partial replacement



(b) S.F was used as an addition

Fig. 5 The effect of S.F on the flexural strength of the mortar specimens

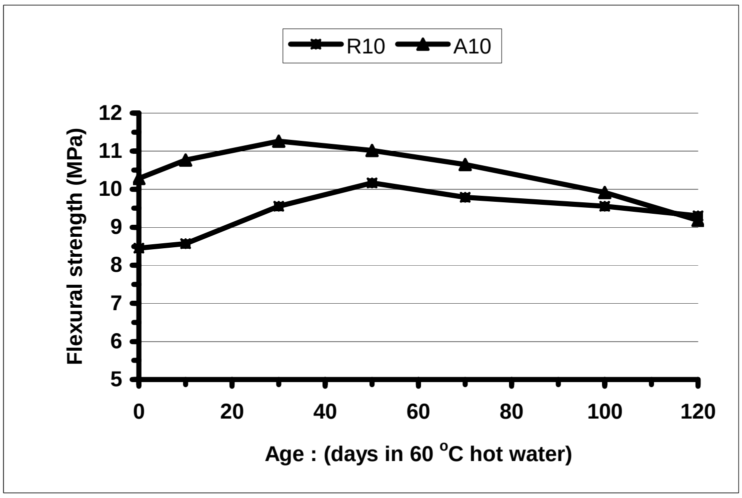


Fig. 6 Flexural strength of mortar specimens with 10% S.F as a replacement and as an addition