Strength prediction of silica fume concrete by accelerated warm-water curing method

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In this paper, the results of a laboratory work predicting the compressive strength of silica fume (SF) concrete by accelerated warm-water curing method (WWM) have been presented. A parametric study has been carried out by producing a total of 48 concrete mixtures with three different cement dosages (350 kg/m³, 400 kg/m³, 450 kg/m³), four different water-cement ratios (0.3, 0.4, 0.5, 0.6) and four SF replacement ratios with cement (0%, 10%, 15%, 20%) on mass basis. Control normal Portland cement (NPC) concrete and SF concrete are cured with accelerated WWM in accordance with ASTM and Turkish standards. The linear relations have been established between accelerated WWM compressive strength and 28-day compressive strength for NPC concrete and SF concrete, separately. Although, the inclusion of SF influences the parameter of prediction equation when compared to NPC concrete, the analyses of the results indicate that prediction of SF concrete compressive strength by accelerated warm-water curing is possible with correlation coefficient ($R^2$) higher than 90%.

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It is known that silica fume (SF) is a by-product of silicon metal or silicon-alloy metal factories. SF, due to its very active and high pozzolanic property, becomes a valuable mineral admixture for cement and concrete. Currently, it is widely used in cement and concrete as a mineral admixture.

On the other hand, there is always a demand of construction industry to get into fast action or motion in the work. However, conventional compressive strength determination usually takes place at 28-day, this period is too long for construction industry. For shortening this period of time, accelerated curing methods were developed to predict 28-day compressive strength of concrete. Three accelerated curing methods covered by ASTM Standard and Turkish standards were boiling water method, warm water method and autogenous curing method.

Tokyay and Atis et al. reported that it was possible to predict 28-day compressive strength of fly ash concrete by warm water and boiling water method. Tokyay proposed a power equation to represent the relationship between accelerated curing compressive strength and 28-day moist cured compressive strength. It was also concluded that the amount of fly ash was not significant in the prediction.

Ozkul studied on the efficiency of accelerated curing in concrete by using normal Portland cement (NPC) and a trass cement. It was concluded that cement type and curing method affect the relation between the 28-day strength and accelerated strength. The aim of this study was to investigate the relationship between WWM accelerated curing compressive strength and moist cured conventional compressive strength of SF concrete. In the present study, only WWM was utilized, as it was reported that warm-water accelerated curing was preferable to boiling water accelerated curing method.

Properties of Materials

Cement

The cement used was ASTM Type I normal Portland cement (NPC) with a specific gravity of 3.16. Initial and final setting times of the cement were 4 and 5 h respectively. Its Blaine specific surface area was 3350 cm²/g and its chemical composition is given in Table 1.

Silica fume

SF was supplied from Antalya-Etibank Ferro-Chrome Factory in Turkey. Its chemical oxide composition is given in Table 1. The specific gravity and unit weight were 2.32 and 245 kg/m³, respectively. The remaining of the SF on 45 µm sieve was 4.8%.
trapped in fresh concrete as per standard. Each control NPC concrete by assuming 2% air was used. The volume of aggregate was determined for water-cement ratios (0.3, 0.4, 0.5, 0.6) were chosen, and its grading is suitable for concrete production. The grading of the mixed aggregate is given in Table 2, which shows that aggregate grading is suitable for concrete production.

Concrete Mixture Proportions
Concrete mixture composition for each concrete is presented in Table 3. Mixture design is made using the absolute volume method given by Turkish Standard. At the beginning of the mixture design, three binder contents (350, 400, 450 kg/m³) and four water-cement ratios (0.3, 0.4, 0.5, 0.6) were chosen, then, the volume of aggregate was determined for each control NPC concrete by assuming 2% air was trapped in fresh concrete as per standard. The volume of aggregate was used to determine the aggregate weight.

Silica fume concretes were produced by modifying NPC concretes. The modification was made by replacing the cement with SF for a given ratio on mass basis. SF replacement ratios were 10%, 15% and 20%. It is known that using SF in concrete reduces the workability of fresh concrete, thus, it is mandatory to use a plasticizer in concrete to maintain the workability for a constant water-cement ratio. In this work, a carboxylic type super-plasticizer (SP) was used a plasticizer in concrete to maintain the workability of fresh concrete, thus, it is mandatory to use a plasticizer in concrete to maintain the workability for a constant water-cement ratio. In this work, a carboxylic type super-plasticizer (SP) was used to maintain the workability of fresh concrete. The grading of the mixed aggregate is given in Table 2 with the standard limit, which shows that aggregate grading is suitable for concrete production.
used at various amounts to maintain the workability of fresh concrete. The amounts of SP used in concrete mixtures are given in Table 3.

Measured unit weight of fresh concrete was in the range of between 2.25 and 2.53 kg/dm$^3$; however, theoretical fresh unit weight determined from mixture proportions was in the range 2.22-2.51 kg/dm$^3$. Flow table workability value of each fresh concrete was in the order of 50 ~60 cm.

Bleeding was observed on the surface of control NPC concrete made with higher cement amount (400, 450 kg/m$^3$) and water-cement ratio (0.5, 0.6). SF concrete did not bleed.

Cubic specimens with 150 mm side were prepared from each fresh concrete. Complete compaction of fresh concrete was obtained by means of vibrating. Three of the cubic specimens were used for the measurements of 28-day compressive strength of concrete cured in water at 23±2°C. Another three of the cubic specimens were used for warm-water accelerated curing strength testing. Sealed cubic specimens were cured at 35°C for 24 h for warm-water method, then; the compressive strengths of cubic specimens were measured within 30 min after WWM accelerated curing. Accelerated strength testing procedure for WWM was carried out in accordance with ASTM standard$^3$ and Turkish Standard$^4$. The strength measurements were carried out for all the mixtures produced.

**Results and Discussions**

Statistical analyses were carried out to establish a relationship between normal standard wet curing compressive strength and accelerated WWM compressive strength. Analyses were carried out for control NPC concrete mixtures, and SF concrete mixtures, separately. The relationship established between normal curing compressive strength and accelerated WWM curing is shown in Fig. 1, for NPC concrete. Figures 2, 3 and 4 represent the relationships established for concrete containing 10%, 15% and 20% SF, respectively. It can be seen from Figs 1-4 that there is an acceptable linear relationship exist between WWM accelerated curing and normal

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![Fig. 1](image1.png)

**Fig. 1** — Relation between WWM and normal curing compressive strength of NPC concrete

![Fig. 2](image2.png)

**Fig. 2** — Relation between WWM and normal curing compressive strength of concrete containing 10% SF

![Fig. 3](image3.png)

**Fig. 3** — Relation between WWM and normal curing compressive strength of concrete containing 15% SF

![Fig. 4](image4.png)

**Fig. 4** — Relation between WWM and normal curing compressive strength of concrete containing 20% SF
curing compressive strength for NPC and SF concrete. Correlation coefficients ($R^2$) were 0.97, 0.93, 0.91 and 0.96 for NPC concrete, and concrete containing 10%, 15% and 20% SF as cement replacement, respectively.

In addition, an attempt was made to establish a relationship between WWM accelerated curing and normal curing compressive strength of SF concrete, using overall SF concrete data. The results are given in Fig. 5. Figure 5 shows that an acceptable linear relationship existed between WWM accelerated curing and normal curing compressive strength of overall SF concrete data with correlation coefficient ($R^2$) 0.94.

Absolute minimum, maximum and average errors of prediction equation for NPC concrete were 0.11, 3.45 and 1.47 MPa, respectively. The upper and lower bands in Fig. 1 are 90% confidence level of the relationship established. Almost all measured NPC concrete data fall in 90% confidence interval, which indicates that prediction equation is useful for concrete industry.

Similarly, absolute minimum, maximum and average errors of prediction equation for overall SF concrete were 0.03, 11.28 and 3.87 MPa respectively. The upper and lower bands in Fig. 5 are 90% confidence level of the relationship established. Again, almost all measured SF concrete data fall in 90% confidence interval, which indicates that prediction equation is useful for concrete industry.

A comparison was made between SF concretes strength prediction equations to evaluate the influence of the SF content on the relations between WWM and normal curing compressive strength. Similarly, another comparison was also made between strength prediction equation of SF concrete and NPC concrete to evaluate the influence of the inclusion of SF in concrete. These comparisons were made by plotting the strength prediction equations of all concretes produced in the same graph (Fig. 6).

It can be seen from Fig. 6 that the inclusion of SF in concrete influences the relationship between WWM accelerated curing and normal curing compressive strength when compared to NPC concrete. There is a large difference between the relationship of NPC concrete and SF concrete. The large difference between WWM strength prediction equation of SF concrete and NPC concrete was attributed to the pozzolanic reaction of SF. However, the changes in the amount of SF are not significant and negligible when comparison takes place between SF concretes made with replacement ratios from 10% to 20%.

Based on above discussions, it was concluded that 28-day compressive strength of SF concrete can be predicted using WWM accelerated curing. The relationships presented in Figs 2, 3 and 4 can be used to predict 28-day compressive strength of SF concrete made with 10%, 15% and 20% replacement, respectively. Additionally, the relationship presented in Fig. 5 could be utilized to predict 28-day compressive strength of SF concrete made with replacement from 10% to 20%. The valid range of compressive strength to be predicted using current relationship is between 45 MPa and 105 MPa.
Conclusions
Following conclusions were made from the study:

(i) There was a large difference between strength prediction equation of SF concrete and NPC concrete.
(ii) The difference is negligible between strength prediction equations of SF concretes.
(iii) The prediction of SF concrete compressive strength by the accelerated warm-water curing was possible with correlation coefficient ($R^2$) higher than 90%.

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