Stress-strain behaviour and flexural strength of silica fume polymer-modified concrete

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Abstract. The adding of silica fume to mix is becoming a huge benefit due to an improvement of mechanical properties. The percent of adding is very important to get targeted mechanical properties. This study investigates the behaviour of polymer modified concrete (PMC) modified with different percentages of silica fume as a percentage of cement weight. Using silica fume powder leads to improve the behaviour of the stress-strain diagram until 10% from the weight of cement, and to increase the values of modulus of elasticity. More dosages of silica fume decrease the modulus of elasticity. The modulus of elasticity increased from 27932 MPa for reference mixes to 43029 MPa for mixes having 10% silica fume powder. Also the of flexural strength increases by increasing silica fume to 12.5%, then after this value is dropped. All of the tensile strength, flexural strength, and modulus of elasticity have been studied in this investigation.

1. Introduction
The usage of polymer modified concrete (PMC) increases since the 70s of the last century [1]. The PMC has more durability [2], fewer voids and more strength than ordinary concrete, using silica fume also can develop the engineering properties such as compressive, tensile strengths, flexural strength and modulus of elasticity of the concrete because of its reaction with calcium hydroxide and forming more gel that fill the cavities and pores inside concrete [3,4,5], to give higher strength and less propagations of micro cracks under loading and to lead to less values of strain and high values of modulus of elasticity. The study of the stress-strain behaviour of concrete is very important in structural design; it can help to estimate the elastic modulus in the straight portion of the stress-strain curve [6]. A higher value of modulus of elasticity indicates less deflection of concrete members. Therefore, the focus of this study is to improve the values of the modulus of elasticity and also the flexural strength of polymer modified concrete.

Furthermore, many kinds of research on Polymer-modified mortars were conducted has been done. The achievement, of polymer-modified mortars, is very high compared with other material. Polymer-modified mortar and polymer-modified concrete made by adding polymer to concrete mix design [7-8]. Silica fume is as finely ground material and it can the water necessary for a certain degree of workability at the low water-cement ratio, thus water-reducing admixture (or super-plasticizer) is often used to improve the workability of mortars with silica fume [9]. The Silica fume (SF) has widely been used as an admixture that used to improve the long-term strength, water absorption, permeability, chloride ion penetration resistance, frost resistance and reducing the heat of hydration. [10-11]. The
cement industry is called the dirtiest industry because it causes great pollution to our environment so this paper is an attempt to reduce this effect by reducing the amount of cement used in the mix.

2. Materials

All mixes were used as Ordinary Portland cement. The crushed coarse aggregate was confirming British standards (B.S 882) as shown in Table 1. The fine aggregate used in this study is from zone 4 as shown in Table 2. 10% of SBR was used in all mixes, and silica fume with a specific density of 2.2 was used also as percentages of cement weight.

| Table 1. Grading of crushed aggregates |
|----------------------------------------|
| Sieve Size (mm) | Percentage of Passing (%) | Passing by Weight Specifications (%) |
|-----------------|---------------------------|-------------------------------------|
| 40              | 100                       | 100                                 |
| 20              | 97.8                      | 95-100                              |
| 10              | 53.3                      | 30-60                               |
| 5               | 2.1                       | 0-10                                |

| Table 2. Grading of fine aggregates |
|--------------------------------------|
| Sieve Size | Percentage of Passing (%) | Passing by weight (zone 4) standards (%) |
|------------|---------------------------|----------------------------------------|
| 10 mm      | 100                       | 100                                    |
| 5 mm       | 97.7                      | 95-100                                 |
| 2.36 mm    | 96.0                      | 95-100                                 |
| 1.18 mm    | 92.5                      | 90 – 100                               |
| 600 micron | 87.1                      | 80 – 100                               |
| 300 micron | 23.2                      | 15 – 50                                |
| 150 micron | 4.9                       | 0-15                                   |

All specimens are cured in water after casting in moulds for 28 days before testing.

3. Specimens and Tests

For a stress-strain relationship test cylinder with dimensions of 150 mm x 300 mm were used, and with mechanical strain gauges to test strain under loads. The specimens were cured for 28 days before testing and tested using a loading rate of 0.254 MPa / sec according to ASTM C-469 [12]. For the indirect tensile test, specimens with dimensions of 100 mm x 200 mm were used to obtain the tensile strength according to Equation 1.

\[ \sigma' = \frac{2P}{\pi DL} \]  

Where, \( \sigma' \): is the maximum tensile strength of concrete, \( P \): is the maximum load from the machine, \( \pi \): is the constant ratio, \( D \): is the diameter of the cylinder, and \( L \): is the height of the cylinder.

Flexural strength tests were done according to British standards [13] where beams with 100 x 100 x 400 mm were used, 3 beams for each mix, and taking the average value. The test for flexural strength was executed by using two-point loading with the value of \( (P/2) \), the flexural strength calculated according to Equation 2.

\[ F_b = \frac{P_1}{bs^2} \]  

Where: \( F_b \): is the flexural (bending) strength, \( P \): is maximum applied load from the machine, \( b \): is the width of the beam, and \( d \): is the depth of the beam.
4. Results and Discussion

4.1 Stress-Strain Diagrams

The stress-strain diagrams were shown in Fig.1 through Fig.6. The stress-strain diagram Fig.1 indicates a compressive strength of 41.6 MPa and modulus of elasticity of 27850 MPa. The modulus of elasticity was found from the linear part of stress-strain curves (initial tangent modulus) by dividing stress value and corresponding strain at the same point. By using a few amounts of silica fume of (2.5%), the stress-strain behaviour shows improvement through increasing compressive strength and decreasing strain values, and increasing modulus of elasticity to 30200 MPa. Table 3 shows the values of the modulus of elasticity by 8.5% for all mixes. From this table, the higher value of modulus of elasticity is noted for a mix with 10 % silica fume, the modulus value was about (43000 MPa). Comparison with reference mix, the increment was 54%, the attributing of this higher increment can be illustrated by the action of silica fume in concrete, the silica fume reaction with calcium hydroxide (Ca(OH)2) that liberated from hydration of cement leads to form another cement gel that fill some voids and cavities in concrete [14] and leads to more improvement in strength and less cracks and cracks propagation under loadings and gives less strain values and higher values of modulus of elasticity according to hooks law $E_c = \sigma / \varepsilon$. Experimental laboratory work of stress-strain relationship shown in Fig.8.

![Stress-strain diagram](image_url)

**Figure 1.** Stress-strain diagram for PMC with 0% SF, $\sigma_{\text{max}} = 41.6$, $\varepsilon_{\text{max}} = 0.00296$, and $E_c = 27932\text{MPa}$. 

Figure 2. Stress-strain diagram for PMC with 2.5% SF, $\sigma_{\text{max}} = 46.92$, $\varepsilon_{\text{max}} = 0.0031$, and $E_c = 30120$ MPa.

Figure 3. Stress-strain diagram for PMC with 5% SF, $\sigma_{\text{max}} = 54.4$, $\varepsilon_{\text{max}} = 0.00328$, and $E_c = 34900$ MPa.
Figure 4. Stress-strain diagram for PMC with 7.5% SF, $\sigma_{\text{max}} = 61.8$, $\varepsilon_{\text{max}} = 0.0034$, and $E_c = 42017 \text{MPa}$.

Figure 5. Stress-strain diagram for PMC with 10% SF, $\sigma_{\text{max}} = 62.7$, $\varepsilon_{\text{max}} = 0.00351$, and $E_c = 43029 \text{MPa}$. 
Figure 6. Stress strain diagram for PMC with 12.5% SF, $\sigma_{\text{max}} = 56.1$, $\varepsilon_{\text{max}} = 0.0041$, and $E_c = 26315$ Mpa.

Figure 7. $f_c - E$ relationships for silica fume polymer-modified concrete.
4.2 Splitting Tensile Strength
Table 3 shows values of indirect tensile strength for all mixes. Highest increment in tensile strength was 98% with 12.5% silica fume mixes; this high increment is due to the same reason discussed above.

| Mix Type       | Silica Fume % | Tensile Strength | Flexural Strength |
|----------------|---------------|------------------|-------------------|
| 1:1.5:2 (10% SBR) | 0.0           | 2.51             | 3.10              |
| 1:1.5:2 (10% SBR) | 2.5           | 3.05             | 3.82              |
| 1:1.5:2 (10% SBR) | 5.0           | 3.58             | 4.38              |
| 1:1.5:2 (10% SBR) | 7.5           | 4.15             | 5.19              |
| 1:1.5:2 (10% SBR) | 10.0          | 4.67             | 5.97              |
| 1:1.5:2 (10% SBR) | 12.5          | 4.97             | 6.69              |
| 1:1.5:2 (10% SBR) | 15.0          | 4.89             | 6.04              |
| 1:1.5:2 (10% SBR) | 17.5          | 4.66             | 5.11              |

4.3 Flexural Strength
Regarding the flexural strength test Table 3, shows that adding silica fume increase the values of strength to more than double. Thus, these higher increments in flexural strength, modulus of elasticity, and compressive strength can give very excellent benefit for the design of structures and can reduce the deflection and also leads to smaller dimensions of concrete members and to more economical its construction.

4.4 Regression Analysis
For a relation between modulus of elasticity and compressive strength, a regression equation shown in Fig. 7 is presented as follows using excel program

\[ E_c = 731.8 \times f_c - 3544 \]  
(3)
Where: \( f_c \) must be of the values between 41.6 MPa and 62.7 MPa.
This regression equation can be used for this type of polymer concrete to find the values of $E$ without a stress-strain test because the modulus of elasticity of concrete can be frequently expressed in terms of the compressive strength of concrete [15-16].

5. Conclusions
Adding silica fume can improve the mechanical properties of polymer modified concrete; give less values of strain and greater values of compressive strength, tensile strength, flexural strength and modulus of elasticity. Using an extra amount of silica fume (more than 10%) may reduce the strength of polymer modified concrete and modulus of elasticity. This can be attributed to the brittleness that results from the addition of silica fume. The stress-strain behaviour became more sharp and more liner with increasing of maximum compressive strength especially with more than 5% of silica fume.

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