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Effect of silica fume and ground pumice on compressive strength and modulus of elasticity of high strength concrete

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HIGHLIGHTS

- This paper presents the results of f_c and E_c of HSC containing SF, GP and SF together with GP.
- The results reveal the use of SF and SF together with GP in the production of HSC.
- The relationship between the f_c and E_c of HSC was also discussed.

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ABSTRACT

This paper presents the results of experimental study on compressive strength and secant modulus of elasticity of high strength concrete (HSC) containing different levels of silica fume, ground pumice and silica fume together with ground pumice. Three concrete series with water–binder ratios of 0.25 and a constant total binder content of 450 kg/m^3 were designed. The compressive strength and secant modulus of elasticity of these concrete series were determined. The experimental results clearly reveal the use of silica fume and silica fume together with ground pumice with a very low water–binder ratio in the production of HSC. The highest compressive strength and secant modulus of elasticity are obtained in the concrete mixtures containing 15% silica fume and 15% silica fume together with 5% ground pumice. The relationship between the compressive strength and secant modulus of elasticity of HSC was also discussed. New two equations for modulus of elasticity of concrete containing different levels of silica fume, ground pumice and silica fume together with ground pumice have been proposed. The experimental results of dependent modulus of elasticity of concrete were compared with the results of various equations proposed by some of national building codes and the authors, and also the results of new equations proposed in this study.

1. Introduction

The use of natural and artificial pozzolans in combination with Portland cement to obtain high strength concrete (HSC) mainly aims at developing concrete microstructure. The microstructure of HSC is more compact as mineral admixture performs as pozzolanic materials. For this purpose, it is well recognized that the use of supplementary cementitious materials, such as silica fume (SF), metakaolin, rice husk ash, ground granulated blast furnace slag and fly ash, are indispensable [1,2]. Most of these supplementary cementitious materials are by products; thus, their inclusion not only serves as an in estimable means to protect environmental resources but also improves concrete construction properties, including its sustainability [3–5]. These pozzolanic materials, when used as mineral admixtures in HSC, can improve the properties of concrete such as the strength, permeability and durability. Concrete containing these pozzolanic materials are used commonly in every place of the world. Some of the major users are power, gas, oil and nuclear industries. The applications of such concrete are increasing with the passage of time due to their superior structural performance, environmental friendliness and low impact on energy employment [1,2].

The properties of concrete such as compressive strength (f_c), modulus of elasticity (E_c) and initial surface absorption are largely influenced by water–binder ratios. Most of the researchers suggest that the water–binder ratio of HSCs needs to be much lower than that of ordinary concrete. While ordinary concrete has a water–binder ratio of 0.50 and higher, generally it is below 0.35 for HSC [6,7]. However, some researchers have improved HSCs at water–binder ratios higher than 0.35 [7,8]. SF increases the water requirement of concrete because of supplement to concrete directly, not a replacement of cement and also its ultra-fineness. Therefore, superplasticisers are used in these concretes to perform the

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required workability; furthermore, different kinds of cement replacement materials are usually supplemented to them because a low porosity and permeability are desirable. SF is the one of the most popular pozzolanas, whose addition to concrete mixtures results in lower porosity, permeability and bleeding because their oxides (SiO_2) react with and consume calcium hydroxide ($Ca(OH)_2$), which is produced by the hydration of ordinary Portland cement. The main results of pozzolanic reactions are: lower heat liberation and strength development; lime-consuming activity; smaller pore size distribution [9].

HSC presents many advantages over conventional concrete. The high f_c can be used advantageously in compression members such as columns and piles. In columns, the reduction in size will lead to decreased constant load on a structure and subsequently to decreased total load on the foundation system. Smaller column size also means more available floor space. HSC can also be effectively used in structures such as plates, shells, and arches where high in-plane compression exists. The relatively higher f_c per unit volume and per unit weight will also significantly decrease the dead load of flexural members [10].

The original purpose of this study is to evaluate the effects of silica fume (SF), ground pumice (GP) and SF together with GP on the f_c and E_c of HSC. For this reason, three series of concrete mixtures (except for control concrete mixture) containing SF, GP and SF together with GP are prepared at the water–binder ratio of 0.25. The f_c and E_c of these concrete mixtures are determined and compared with each other. Two equations relating to the E_c and f_c of these concrete mixtures containing SF, GP and SF together with GP are also developed based on the experimental evaluation. These equations are developed for 150 × 300 mm concrete cylinders. Moreover, a detailed comparison of these equations with the CEP-FIP-MC90 [11], ACI-363-92 [12], Norwegian [13], Ahmad and Shah [14], Iravani [15], and Rashid et al. [10] equations is also made.

2. Materials used in the experimental study

2.1. Cement

The cement used was CEM I 42.5 R ordinary Portland cement, which correspond to TS EN 197-1 [16]. Specific gravity of cement used was 3.08. Initial and final setting times of the cement were 130 min and 215 min, respectively. Its Blaine specific surface area was 3310 cm^2/g and its chemical composition is given in Table 1.

2.2. Silica fume

The silica fume (SF) used 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 2.30 and 247 kg/m^3, respectively.

2.3. Ground pumice

The ground pumice (GP) used was supplied from Nevşehir Miromin in Turkey. Its chemical oxide composition is given in Table 1. The specific gravity and unit weight were 2.33 and 265 kg/m^3, respectively.

2.4. Aggregate

The fine aggregates used as both natural river sand (NRS) and natural crushed limestone-I (CL-I) have a maximum particle size 5 mm, with a specific gravity of 2.48 and 2.54, respectively. The coarse aggregates were natural crushed limestone-II (CL-II) and natural crushed limestone-III (CL-III), with size of 5–12 mm and 5–22 mm, with a specific gravity of 2.70 and 2.72, respectively. The particle size, specific gravities and mixing ratios of the aggregates used are also given in Table 2.

Table 2
The particle size, specific gravity and mixing ratio of aggregates.

Aggregate code[a]	Particle size (mm)	Specific gravity	Mixing ratio (%)
NRS	0–5	2.48	25
CL-I	0–5	2.54	25
CL-II	5–12	2.70	10
CL-III	5–22	2.72	40

[a] NRS = natural river sand, CL = crushed limestone.

2.5. Superplasticizer

The superplasticizer admixture was a polycarboxylic acid based (Glenium 51, BASF) with specific gravity between 1.075 and 1.115. Glenium 51 is considered one of the new generations of copolymer-based superplasticizers. ASTM C 494 [17] designed for the production of HSC was used in this study.

2.6. Concrete mixtures

Three series of concrete mixtures, which was apart from the control concrete mixture, were prepared and tested to evaluate the f_c and E_c. A total of 22 concrete mixtures were prepared in these series. In the first and second series, SF and GP were used to replace 5%, 10%, 15%, 20% and 25% by weight of Portland cement. In the third series, SF was used together with GP to replace different ratios (2.5%SF + 2.5%GP; 5%SF + 5%GP, 5%SF + 10%GP, 5%SF + 15%GP and 5%SF + 20%GP; 10%SF + 5%GP, 10%SF + 10%GP and 10%SF + 15%GP; 15%SF + 5%GP and 15%SF + 10%GP; and 20%SF + 5%GP) by weight of Portland cement. The total cementitious materials content used in these mixtures was kept constant at 450 kg/m^3 and the water–binder ratio at 0.25. The details of the concrete mixtures are given in Table 3. In order to keep a constant water–binder ratio, superplasticizer was used in different ratios. All concrete mixtures had the same workability with a slump of 140 ± 20 mm. The concrete mixtures were mixed for a total of 5 min in a laboratory pan mixer. From each concrete mixture, 150 × 300 mm cylinder was molded for the determination of the f_c and E_c. Molding of cylinder was conducted in three layers. Each layer was compacted by internal vibration and top surface was leveled and smoothed using a trowel. After casting, each of the specimens was allowed to stand for 24 h in laboratory. At the age of 24 h, the specimens were removed from the molds and cured in lime saturated water at 23 ± 2 °C until the date of testing. The test specimens were cured according to ASTM C 192 [18].

2.7. Test methods

Three cylinders, 150 mm in diameter and 300 mm in height, were used for f_c and E_c tests. The f_c of each specimen was determined according to ASTM C 39 [19] and TS EN 12390-3 [20]. The E_c of each specimen was determined according to ASTM C 469 [21] and TS 3502 [22]. The specimens were tested in uniaxial compression at a constant rate of loading 3.5 kN/s. The compressive load was applied using a servo-controlled hydraulic testing machine of 3000 kN capacity. The stress–strain characteristics were determined after 28 days of curing. The E_c was measured as a secant modulus in the elastic range. Each of these specimens was fitted with a compressometer containing a dial gage capable of measuring deformation to 0.002 mm and then loaded three times to 40% of the ultimate load of companion cylinder. The first set of readings of each cylinder was discarded and the modulus was reported as the average of the second sets of readings. Following the third loading of each specimen, the compressometer was removed and the specimen was loaded to failure to determine the f_c.

3. Results and discussion

3.1. Properties of fresh concrete

The workability of fresh concrete including slump was measured and unit weight of the fresh concrete was determined after

Table 1
Chemical composition of cementitious materials.

Oxide	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	K_2O	Na_2O	LOI[a]
Cement	21.20	5.90	2.10	62.10	2.30	3.40	0.80	0.40	1.80
Silica fume	85.98	0.65	0.32	0.70	4.91	0.63	–	–	2.66
Ground pumice	71.80	12.40	1.05	1.10	0.34	0.08	4.51	5.20	3.52

[a] LOI = loss on ignition (%).