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Effect of pozzolanic materials and curing methods on the elastic modulus of HPC

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Abstract

The modulus of elasticity of a material is a fundamental property required for the proper modeling of its constitutive behavior and for its proper use in various structural applications. This paper discusses experimental evaluation of the elastic modulus of high-performance concrete made from mixes using various percentages of fly ash, silica fume, and granulated blast furnace slag. Results are compared to those from control specimens at various ages between 1 and 90 days. The results presented are part of a study for the New Jersey Department of Transportation (NJDOT) to develop and implement High-Performance Concrete (HPC) mix design and technical specifications for transportation structures. The study also investigates the effect of curing on the elastic modulus. Three methods of curing were evaluated: (1) air-dry curing, (2) curing compound, and (3) wet curing with burlap. The results showed that adding silica fume resulted in an increase in strength and modulus at early ages, however, there was no change in the modulus at 28 and 56 days. In addition, adding 20% fly ash with various percentage of silica fume had an adverse effect on both strength and modulus values at all ages to 90 days. It is also shown that dry curing and curing compound reduce the modulus of elasticity compared to wet curing with burlap. Results showed the elastic modulus of HPC is proportional to the compressive strength, but the prediction equations of ACI-318 and ACI-363 may not accurately predict the modulus values for high-performance concrete with pozzolans.

Keywords: Elastic modulus; High-performance concrete; Compressive strength; Curing methods; Fly ash; Silica fume; Slag

1. Introduction

High-perfromance concrete is one of the most significant new materials available to federal, state, and local agencies, and the general public to utilize in new construction and in rehabilitation of buildings, highways, and bridges. With the rapid increase in the use of this new material, there is a need to accurately predict its properties such as elastic modulus, shrinkage, creep, permeability, and durability. One of the important properties needed for the successful application of these mateirals in structures is the modulus of elasticity. The elastic modulus is needed by designers for stiffness and deflections evaluations. Predicting the elastic modulus is also important in reinforced and prestressed concrete for shrinkage and creep evaluation as well as crack control especially at an early age [1,2]. In order to effectively use high-performance concrete, there is a need to accurately predict its elastic modulus and to study the effect of the addition of pozzolanic materials and curing methods on this important material property.

Studies have shown [3–6] that adding pozzolans enhances the strength and durability of concrete. The strength of high-performance concrete is reduced with

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the addition of fly ash at early age. Experimental results from this study have shown that the elastic modulus of HPC using fly ash were lower than those without fly ash at early age. This also can be related to the reduction of strength and the proportional relationship between modulus and compressive strength. Baalbaki et al. [8] performed a study on high-strength concrete (HSC) using silica fume and 0.27 w/(c + p) ratio. They concluded that until a better and more reliable prediction of the elastic modulus of HSC is available, the best method is to use direct measurements. They also concluded that this situation would continue until we understand the effect of all the constituent materials of HSC and their combinations. Thus, an accurate prediction of the modulus of elastcity of HPC would be to measure the modulus values for many specimens in every project; which is not practical and more expensive. Moreover, it will be difficult to measure concrete modulus at very early age [1] with potential damage to specimen and variablity of results. Najm and Naaman [9] measured the elastic modulus of High Performance Fiber Reinforced Cement-based Concrete (HPFRCC) in tension and compression and concluded that the elastic modulus of a composite material is greatly affected by the range over which it is measured and that the modulus values in compression are less variable than those in tension. They also concluded that multiple cracking (early shrinkage cracking) had an effect on the elastic modulus of HPFRCC in tension and that needs further investigation to minimize the errors in any prediction model.

The effect of curing on strength and other properties of HPC has been studied by Nassif, Suksawang, and Mohamad [3,7] and their results showed that wet curing with burlap curing (referred to as burlap curing hereafter) resulted in higher strength than air-dry curing and using a curing compound. Their results also showed curing methods will have a long term effect on strength and modulus that need to be further evaluated. The effect of curing on the elastic modulus of HPC was part of this experimental study. This paper discusses the experimental evaluation of the elastic modulus of high-performance concrete made with various percentages of pozzolans, various water-to-cement-and-pozzolans (w/(c + p)) ratios, and various curing methods compared to control specimens at 3, 7, 14, 28, and 90 days.

The experimental program comprised three series of specimens: series I, series II, and series III. Series I included concrete mixes with 0.39 w/(c + p) ratio (water to cement + pozzolan ratio) that were tested for the effect of pozzolans on the compressive strength and elastic modulus at various ages. Series II included concrete mixes with various w/(c + p) ratios and variable percentages of pozzolans. Series III included concrete mixes with 0.29 and 0.35 w/(c + p) ratios and different percentages of pozzolans cured using three different methods: (1) air-dry curing, (2) curing compound, and (3) wet burlap.

The objective of this study, is to evaluate the effects of pozzolans such as FA (fly ash), SF (silica fume), and GBFS (granulated blast furnace slag) and the effect of curing methods on the elastic modulus of HPC and its variation with time. An equation relating the elastic modulus, E, and concrete strength, f'_c, is developed based on the experimental evaluation. Moreover, a detailed comparison of this equation with the ACI-318 and ACI-363 equations is also made.

2. Research significance

High-performance concrete (HPC) is one of the most significant emerging materials available to federal, state, and local agencies, and the general public to utilize in new construction and in rehabilitation of buildings, highways, and bridges. In order to safely and effectively use HPC, its stress–strain behavior must be known with the compressive strength and modulus of elasticity modulus being two of the most important properties of this response. Furthermore, the knowledge of the modulus of elasticity at early age and how it changes with time is important for predicting long-term effects and durability of concrete structures. Thus, there is a need to evaluate the modulus of elasticity and study the factors that influence its prediction with time.

3. Experimental program

3.1. Materials

Several series of concrete mixes were made and tested to evaluate the modulus of elasticity. The mix proportions of these mixes are presented in Table 1 for series I, Table 2 for series II, and in Table 3 for series III. Series I mixes were selected from an array of mixes (a total of 64 mixes) having various proportions of FA (fly ash) and SF (silica fume) and constant w/(c + p) ratio. The objective was to optimize the percentage of FA and SF required for optimum shrinkage and strength results. Series I and II mixes were moist cured in a curing room at 24 °C and 98% relative humidity. Series II specimens were prepared to study the effect of FA and SF on the compressive strength and elastic modulus using variable w/(c + p) ratio. Series III specimens were cured using three different curing methods: (1) air-drying curing, (2) curing compound, and (3) wet burlap. Fig. 1 shows the specimens stored in an environmental chamber (10 m × 8 m) where the relative humidity (RH) and temperature were kept at 50% and 24 °C, respectively. The curing compound was applied to the exposed concrete surfaces of the specimens while the burlap was kept

Table 1
Mix proportions and compressive strengths for series I specimens

Mix	Control	S[a]0F[b]10	S0F20	S0F30	S5F0	S10F0	S15F0	S5F10	S5F20	S10F20	S15F20
Type I cement (kg/m^3)	477	429	382	334	453	429	405	405	358	334	310
Sand (kg/m^3)	701	701	701	701	701	701	701	701	701	701	701
Gravel (kg/m^3)	1022	1022	1022	1022	1022	1022	1022	1022	1022	1022	1022
Fly Ash Class F (kg/m^3) (%)	0	48 (10%)	95 (20%)	143 (30%)	0	0	0	48 (10%)	95 (20%)	95 (20%)	95 (20%)
Silica fume (kg/m^3) (%)	0	0	0	0	24 (5%)	48 (10%)	72 (15%)	24 (5%)	24 (5%)	48 (10%)	72 (15%)
Slag (kg/m^3)	0	0	0	0	0	0	0	0	0	0	0
Water (kg/m^3)	186	186	186	186	186	186	186	186	186	186	186
w/(c + pozzolans)	0.39	0.39	0.39	0.39	0.39	0.39	0.39	0.39	0.39	0.39	0.39
Superplasticizer (ml/m^3)	3267	3267	2614	1960	3920	4901	5227	5227	4574	4574	4901
AEA (ml/m^3)	523	523	523	523	627	627	627	523	523	523	627
Air content (%)	2	6	5	2	4	3	2	3	2	7	5
Slump (mm)	76.2	152.4	82.55	76.2	57.15	63.5	44.45	25.4	82.55	127	82.55
28 Days f_c' (MPa)	47.0	49.0	44.0	43.0	52.0	53.0	50.0	55.0	46.0	38.0	40.0

[a] S = silica fume.
[b] F = fly ash.

Table 2
Mix proportions and compressive strengths for series II specimens

Mix	A2	A3	B1	B6	C2	C3	B1N	D1	D3	G1	G2
Type I cement (kg/m^3)	360	338	371	347	427	402	402	441	453	500	513
Sand (kg/m^3)	745	745	701	701	679	679	679	630	630	584	584
Coarse agg. (kg/m^3)	1022	1022	1022	1022	1022	1022	1022	1022	1022	1022	1022
Fly Ash Class F, kg/m^3(%)	42 10%	63 15%	71 15%	86 18%	50 10%	75 10%	75 15%	85 15%	85 15%	96 15%	64 10%
Silica fume, kg/m^3 (%)	21 5%	21 5%	33 7%	43 9%	25 5%	25 5%	25 5%	40 7%	28 5%	48 7%	32 5%
Slag, kg/m^3 (%)	0	0	0	0	0	0	0	0	0	0	0
Water (kg/m^3)	186	186	186	186	186	186	186	186	186	186	186
w/(c + pozzolans)	0.44	0.44	0.39	0.39	0.37	0.37	0.35	0.33	0.33	0.29	0.29
Superplasticizer (SP) (m^1/m^3)	2206	2206	3106	3106	4920	3280	6932	6621	6621	9208	8371
AEA (ml/m^3)	414	414	466	466	492	492	520	552	552	628	628
Air content (%)	4.25	2.5	7.5	3	5	4	5	3.5	4	3.5	3
Slump (mm)	57.2	44.5	146	76	76	25.4	135	89	102	102	44.5
28 Days f_c' (MPa)	38.2	33.8	48.0	46.6	47.6	53.4	65.4	70.2	59.0	73.5	73.5

Table 3
Mix proportions and compressive strengths for series III specimens

Mix	L1	L2	L3	L4	M1	M2	M3	M4
Type I cement (kg/m^3)	642	499	499	642	532	532	414	414
Sand (kg/m^3)	455	455	455	310	555	555	555	555
Coarse agg. (kg/m^3)	1022	1022	1022	(LWA) 515	1022	1022	1022	1022
Fly Ash Class F (kg/m^3)(%)	–	143 20%	–	–	–	–	118 20%	–
Silica Fume (kg/m^3) (%)	71 10%	71 10%	71 10%	71 10%	59 10%	59 10%	59 10%	59 10%
Slag (kg/m^3) (%)	–	–	143 20%	–	–	–	–	118 20%
Water (kg/m^3)	207	207	207	207	207	207	207	207
SP (ml/m^3)	10226	10226	10226	10226	7705	4621	4621	4621
AEA (ml/m^3)	927	927	927	927	768	768	768	768
Air content (%)	2.5	6.75	2.25	1.75	7.5	4	6.5	2
Slump (mm)	64	203	32	89	197	102	178	114
w/(c + pozzolans)	0.29	0.29	0.29	0.29	0.35	0.35	0.35	0.35

Fig. 1. Test specimens and various curing methods.

wet every 24 h. In addition, GBFS (blast-furnace slag) was introduced in mixes L3 and M4 of series III specimens. The cement used was Allentown Portland cement conforming to ASTM Type I cement specifications with a specific gravity of 3.15. The coarse aggregates, with the exception of mix L4, were New Jersey crushed granite with a maximum size 9.5 mm, a unit weight of 1572 kg/m^3, a specific gravity of 2.8, and 1.2% absorption. Mix L4 uses lightweight aggregates from Solite Corporation in New York. The Solite aggregate is an expansive shale with maximum size of 19 mm, a unit weight of 793 kg/m^3, a specific gravity of 1.2, and 9% absorption. The fine aggregates were concrete sand with a specific gravity of 2.56 and 0.36% absorption and were obtained from the same source as the coarse aggregates. The pozzolanic materials consisted of ASTM Class F fly ash with a specific gravity of 2.49 and particle size ranging from 1 to 100 μm with high silica and alumina content. The other pozzolanic material were granulated blast furnace slag and silica fume. The silica fume is made from densified micro-silica powder with a specific gravity of 2.22. The granulated blast furnace slag had a specific gravity of 2.8. Admixtures included water-reducing agents, high-range water-reducing agent, and air-entraining agents.

3.2. Mixing procedures

Fine and coarse aggregates were added together in the mixer. Then one-third of the water was added followed by the air-entraining agent. Cement is then added (after 30 s) along with the rest of water and followed by the pozzolanic materials. The concrete was mixed in the mixer with all the ingredients for about three to four minutes. Then the superplasticizer was added and the mix was allowed to mix for three more minutes. The batch was then placed in plastic cylinders 100 mm × 200 mm in three layers while vibrating the specimens. The cylinders for series I and II were demolded after 24 h and the specimens were wet cured in the curing room until time of testing. For each mix, approximately 28 cylinders were prepared and tested for strength and modulus. Slump tests and air content tests were conducted on fresh concrete following ASTM C143 and C173, respectively. The hardened specimens were capped with sulfur compound at both ends to distribute the load uniformly over the top and bottom areas of the cylinder.

3.3. Testing procedures

The compressive strength tests are done in accordance with ASTM C-39 [10]. Three 100 mm × 200 mm cylinders were tested for strength at 1, 3, 7, 14, and 28 days and three cylinders were tested for the modulus of elasticity at 3, 7, 14, and 28 days. Tests for strength and modulus were carried out on the same day using a 1780 kN Tinius-Olsen hydraulic testing machine equipped with a swivel-head platen. The strain was measured over a 100 mm central gage length using two digital dial gages attached on opposite sides around the perimeter of the specimen. All specimens tested for modulus were subjected to identical initial loadings regardless of the compressive strength. This initial cycle of loading and unloading was repeated at least twice before the specimen was loaded to the desired load level. The tests on modulus of elasticity were loaded to a maximum stress equal to 40% of the maximum compressive strength according to ASTM C469 [11]. The loading rate was constant at 0.2–0.24 MPa/s. The load and the deformation were recorded for each specimen and the value of the elastic modulus was calculated from recorded loads and deformations according to ASTM. Test specimens and various curing methods are shown in Fig. 1. For all series, strength and modulus tests were conducted at 3, 7, 14, and 28 days. In addition, for Series I, modulus tests were also conducted at 56 days and for series III, where curing methods were evaluated, strength and modulus tests were conducted at 1 day.

4. Results and discussion

The compressive strength and the modulus of elasticity of series I are summarized in Table 4 for 3, 7, 14, and 28 days. Results of specimens in series II and III are shown in Tables 5 and 6 respectively. Results from series I showed that the strength as well as modulus values were lower for mixes with higher percentages of fly ash. Fig. 2 illustrates that the concrete containing fly ash has a lower compressive strength than that in normal concrete, however, for all mixes, the elastic modulus is higher than that of normal concrete at both early- and later-ages. In addition, for all mixes, the addition of fly ash beyond 10% decreases both the compressive strength

Table 4
Compressive strength and elastic modulus of series I specimens

Mix	Control	S[a]0F[b]10	S0F20	S0F30	S5F0	S10F0	S15F0	S5F10	S5F 20	S10F20	S15F20
Compressive strength (MPa)											
1 Day	19.8	21.4	19.4	15.0	29.0	30.5	25.1	27.6	22.3	13.9	14.0
3 Days	36.6	32.3	29.3	26.8	39.6	39.6	39.2	36.5	29.3	21.5	24.9
7 Days	40.0	40.1	36.0	30.8	45.9	43.5	40.7	43.9	32.9	29.4	28.7
14 Days	43.8	41.6	39.0	35.5	44.2	46.9	46.6	50.8	41.1	32.9	36.8
28 Days	46.6	49.4	44.2	42.7	52.4	53.4	50.1	54.9	46.0	38.1	39.8
56 Days	52.2	53.1	51.0	48.7	57.6	58.8	56.7	57.8	49.6	42.5	47.5
90 Days	54.6	57.1	56.1	52.1	54.5	57.3	52.1	64.5	53.6	42.1	46.8
Elastic modulus (GPa)											
3 Days	24.0	26.2	26.1	24.3	28.6	28.5	25.8	27.0	24.0	22.0	22.6
7 Days	27.3	30.8	29.6	27.7	31.2	30.3	26.7	29.4	25.2	22.4	24.5
14 Days	27.7	31.9	29.0	29.2	31.8	31.5	30.4	30.0	26.7	22.6	26.8
28 Days	31.8	37.1	31.6	30.7	32.0	31.9	34.3	30.8	27.7	26.2	27.1
56 Days	36.0	38.3	38.3	37.5	34.2	35.6	34.9	33.4	30.3	30.1	30.6
E/E (control)											
3 Days	1.00	1.09	1.09	1.01	1.19	1.19	1.07	1.12	1.00	0.91	0.94
7 Days	1.00	1.13	1.08	1.01	1.14	1.11	0.98	1.08	0.92	0.82	0.90
14 Days	1.00	1.15	1.05	1.05	1.15	1.14	1.10	1.09	0.97	0.82	0.97
28 Days	1.00	1.17	1.00	0.96	1.01	1.00	1.08	0.97	0.87	0.82	0.85
56 Days	1.00	1.06	1.06	1.04	0.95	0.99	0.97	0.93	0.84	0.84	0.85
Average	**1.00**	**1.12**	**1.06**	**1.02**	**1.09**	**1.09**	**1.04**	**1.04**	**0.92**	**0.84**	**0.90**
$E/(f'_c)^{1/2}$											
3 Days	3967	4613	4821	4697	4553	4538	4116	4471	4437	4731	4528
7 Days	4318	4858	4924	4988	4604	4588	4190	4440	4388	4126	4566
14 Days	4180	4942	4648	4897	4793	4603	4444	4218	4169	3946	4410
28 Days	4654	5275	4760	4691	4427	4370	4837	4155	4086	4243	4281
56 Days	4872	5068	5116	5293	4633	4648	4642	4155	4133	4648	4447
Average	**4398**	**4951**	**4854**	**4913**	**4602**	**4549**	**4446**	**4288**	**4243**	**4339**	**4446**

[a] S = silica fume.
[b] F = fly ash.

Table 5
Compressive strength and elastic modulus of series II specimens

Mix design	A2	A3	B1	B6	C2	C3	B1N	D1	D3	G1	G2
Elastic modulus (GPa)											
3 Days	24.2	22.8	N/A	28.7	29.9	25.5	30.5	N/A	28.5	31.9	31.0
7 Days	26.6	22.4	28.0	28.7	31.2	31.7	31.7	33.0	31.4	N/A	34.1
14 Days	28.5	22.9	32.7	29.8	34.6	34.9	34.4	34.6	33.4	N/A	35.9
28 Days	29.8	26.5	30.8	32.1	35.5	33.9	33.8	N/A	35.4	37.6	37.9
Compressive strength (MPa)											
3 Days	24.0	22.3	N/A	38.6	39.1	36.1	43.1	47.3	48.6	49.4	49.4
7 Days	27.9	25.5	33.5	37.1	42.8	35.2	50.7	56.3	53.9	60.5	60.5
14 Days	35.3	28.9	36.4	44.2	51.4	49.6	57.5	62.8	58.9	70.0	70.0
28 Days	38.2	33.8	48.0	46.6	47.6	53.4	65.4	70.2	59.0	73.5	73.5

and elastic modulus of concrete. Moreover, comparing the ratios of elastic modulus of each specimen to the control in series I, it is observed that specimens with 10% FA increased the elastic modulus by 6–17% for all ages. This comparison is shown in Table 4. In addition, specimens with 20% FA had on average a 6% increase in modulus. This observation confirms that the addition of FA beyond 10% does not greatly enhance the modulus. Moreover, adding more than 20% FA, as shown in the case of the specimens with 30% FA, will have, on average, practically no effect on the modulus. Therefore, based on the results of this study, the optimum percent of added FA to enhance the modulus is 10%.

The effect of water-to-cement ratio on strength and modulus from series II is shown in Fig. 3. In this figure,

Table 6
Compressive strength and elastic modulus of series III specimens

Mix	Curing method	Compressive strength, f'_c (MPa)					Elastic modulus, E (GPa)				
		No. of days					No. of days				
		1	3	7	14	28	1	3	7	14	28
L1	B[a]	40.9	51.3	62.0	68.7	70.3	29.6	35.3	30.4	37.1	36.2
	C[b]	37.0	53.6	59.0	60.8	67.5	32.4	32.0	31.8	30.7	28.0
	D[c]	41.0	50.1	57.1	60.1	62.8	29.6	31.9	27.8	31.6	32.6
L2	B	26.9	40.6	46.8	51.3	59.8	32.6	30.5	30.5	30.6	33.5
	C	27.7	42.8	46.2	47.7	51.0	29.2	27.1	27.9	28.5	24.8
	D	26.1	38.6	41.3	49.0	49.9	27.6	28.4	28.4	29.4	26.3
L3	B	46.8	59.0	57.9	66.9	64.8	32.8	34.4	35.1	35.6	37.2
	C	40.1	54.6	57.6	60.1	61.5	30.1	32.7	30.5	32.3	29.6
	D	46.2	52.1	51.6	51.7	60.4	29.6	27.8	30.7	29.6	28.1
L4	B	23.1	37.9	35.7	38.4	38.7	15.3	16.0	17.1	16.0	N/A
	C	23.9	32.9	36.2	36.5	38.4	17.4	14.8	13.2	14.4	N/A
	D	22.6	34.0	34.9	35.4	37.3	15.0	14.9	14.7	15.8	N/A
M1	B	37.6	41.8	45.3	46.1	56.5	28.2	29.3	30.6	29.0	32.2
	C	30.0	41.3	46.0	48.3	49.9	25.9	28.7	28.8	28.1	26.0
	D	23.8	42.3	41.6	38.4	46.3	28.1	27.8	25.7	24.7	24.0
M2	B	40.6	47.1	51.6	56.5	60.1	29.5	32.6	35.7	32.4	N/A
	C	39.1	44.6	49.8	52.9	53.5	29.9	33.5	30.1	29.6	N/A
	D	37.3	46.1	49.9	53.1	59.2	29.1	31.3	29.5	27.7	N/A
M3	B	24.3	30.5	34.0	37.3	45.2	23.5	27.1	25.6	30.0	N/A
	C	23.5	31.8	33.5	36.2	38.4	22.5	25.3	23.3	24.4	N/A
	D	23.0	30.5	33.5	36.8	39.1	23.1	25.4	23.7	22.5	N/A
M4	B	33.1	42.8	48.9	54.3	63.8	30.9	28.4	32.4	34.5	N/A
	C	40.6	42.0	49.4	53.5	51.0	26.3	26.8	29.3	29.0	N/A
	D	29.4	38.4	41.7	50.2	54.1	29.0	29.8	29.1	26.5	N/A

[a] Wet burlap.
[b] Curing Compound.
[c] Air-dry curing.

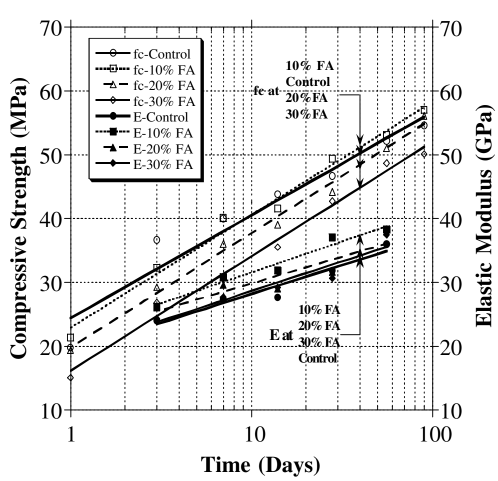

Fig. 2. Variation of concrete strength and elastic modulus with time for various percentage of fly ash for specimens in series I.

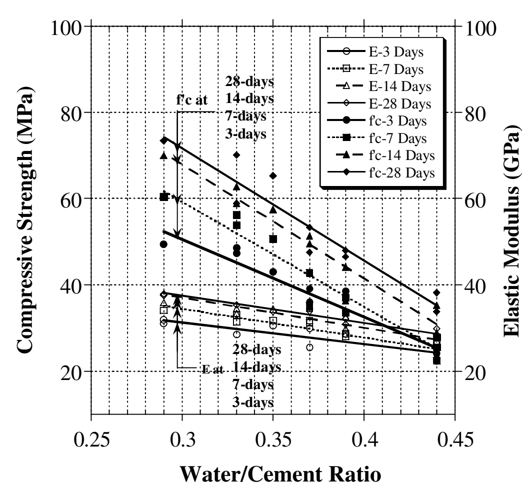

Fig. 3. Variation of concrete strength and elastic modulus with water-to-cement ratio for specimens in series II.

it is observed that the water-to-cement ratio has a more pronounced effect on the compressive strength than on the elastic modulus.

Fig. 4 shows the variation of the compressive strength and the elastic modulus with various percentage of silica fume (5%, 10%, and 15%) from specimens in series I.

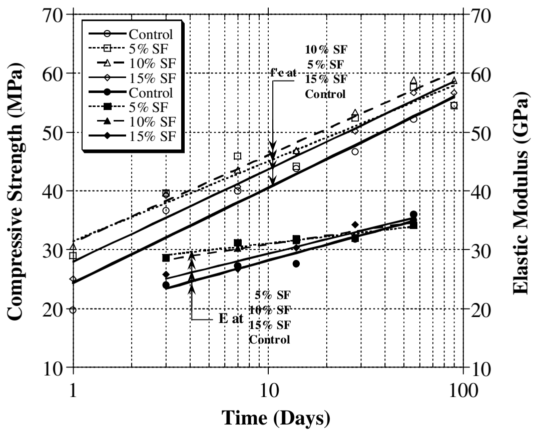

Fig. 4. Variation of concrete strength and elastic modulus with time for various percentage of silica fume for specimens in series I.

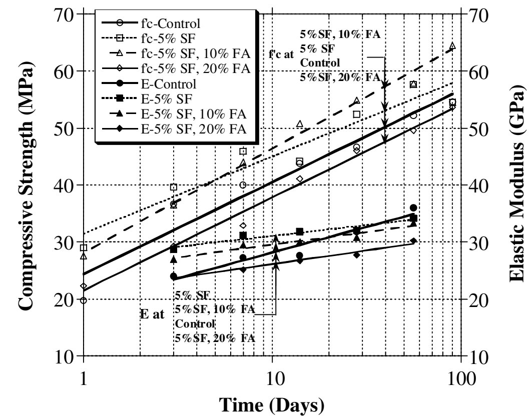

Fig. 5. Variation of concrete strength and elastic modulus with time for 5% silica fume and various combinations of fly ash for specimens in series I.

Results illustrate that the concrete strength increases with the addition of silica fume at early age and at 28 days. The elastic modulus, on the other hand, increases at early ages only and the increase becomes less at 28 and 56 days. The elastic modulus at 28 and 56 days seems to approach the control values. Table 4 shows that compressive strength and modulus data for various percentages of silica fume (5%, 10%, and 15%) but with no fly ash. The ratio of elastic modulus of various specimens relative to the control in Series I is also shown in Table 4. It is observed that specimens with 5% SF and 10% or less FA, had a higher elastic modulus by about 10–20% at early age (3–14 days) but then it decreases to become close to the control at 28 and 56 days. A similar trend was observed for specimens with 10% SF and no FA. This observation confirms that the addition of silica fume beyond 5% does not greatly enhance the modulus. Moreover, adding more than 10% SF, as shown in the case of the specimens with 15% SF, will have, on average, a minimal effect on the modulus. Therefore, based on the results of this study, it seems that the optimum percentage of SF to enhance the modulus would be between 5% and 10%.

Fig. 5 shows that adding a combination of fly ash and silica fume can improve both strength and elastic modulus. Among the fly ash and silica fume combinations tried in series I, it was observed that the best combination for improving compressive strength and modulus is the mix with 5% SF and 10% FA. This combination increased the strength at 28 and 90 days and increased the modulus at early age (3 days) but showed no change in the modulus at 28 days relative to the control. At 56 days, there seems a slight reduction in the modulus. It was also noticeable that adding more than 10% FA decreases both strength and modulus in comparison with control specimens.

Fig. 6 shows a comparison of results for mixes having equal percentage of fly ash or silica fume. It was observed that mixes with 10% fly ash and no silica fume

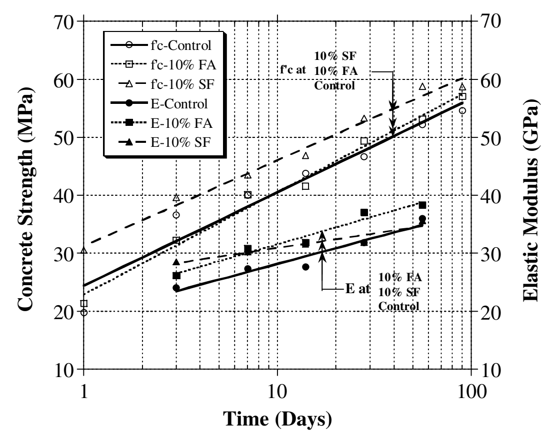

Fig. 6. Variation of concrete strength and elastic modulus with time for 10% silica fume and 10% fly ash for specimens in series I.

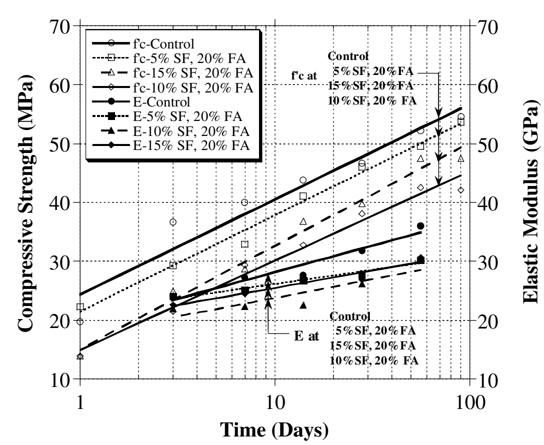

Fig. 7. Variation of concrete strength and elastic modulus with time for various percentage of silica fume and 20% fly ash for specimens in series I.

did not have a significant effect on the strength; however, it produced an increase in the elastic modulus at all ages. In comparison, the mixes with 10% SF and no FA seemed to have an increase in strength at all ages but an increase in modulus at early ages only. Fig. 7 shows results for mixes with combinations having 20% FA and various percentages of SF. In comparison with control specimens, the compressive strength and elastic modulus decreased for all combinations.

5. Effect of curing methods

The effect of curing methods on the elastic modulus was also investigated in this study. Test results showed that using burlap curing would result in higher elastic modulus of concrete compared to air-dry curing or using a curing compound. This would be expected because of the increase of strength and the reduced shrinkage with the use of burlaps. The results showed that without the proper curing the modulus of elasticity could be lower at 28 days than at 14 days. Fig. 8 shows the modulus of elasticity using burlap curing continues

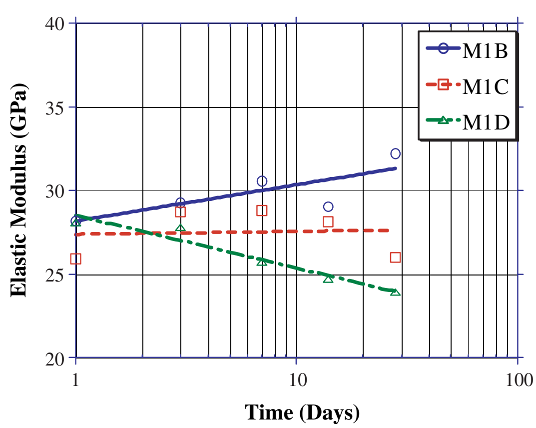

Fig. 8. Variation of elastic modulus with time for various curing methods using silica fume for specimens in series III.

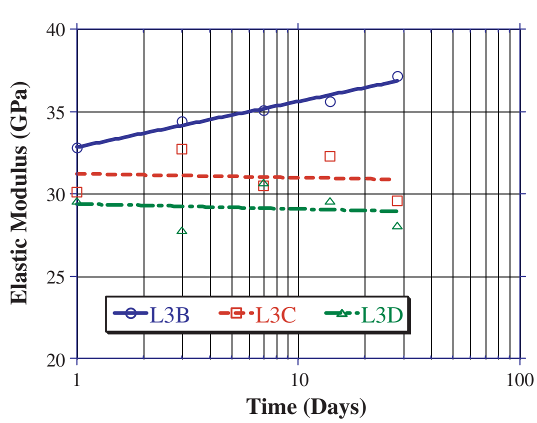

Fig. 9. Variation of elastic modulus with time for various curing methods using granulated blast-furnace slag and fly ash for specimens in series III.

to increase with age while with air-dry curing and compound curing there is no increase and rather showed some decrease. This trend was also observed for both fly ash and slag. The effect of curing method on mixes using granulated blast furnace slag is shown in Fig. 9. The compressive strength also was higher using burlaps compared to air-dry and curing compounds, however, all three curing methods showed an increase of compressive strength with age. This observation needs further investigation because it seemed that the method of curing had different effects on compressive strength than on the elastic modulus.

6. Comparison with ACI code equations

The elastic modulus from test results is compared to the prediction equations of ACI 318-02 [12] and ACI 363 [13] to evaluate the accuracy of these equations in predicting the modulus values when pozzolans are added to the concrete and when the curing methods are changed. The ACI 318-02 prediction equation for the elastic modulus of concrete tested at 28 days, having an average unit w_c is the density of concrete in kg/m^3 and f'_c is the cylinder compressive strength at 28 days in MPa, as a function of its compressive strength is given by:

$$E_c = 0.0427(w_c)^{1.5}\sqrt{f'_c} \quad \text{for } f'_c \leqslant 42 \text{ MPa} \tag{1}$$

The modulus of elasticity at an early age from the test data from Series I, II, and III versus the square root of the compressive strength and the ACI 318-02 equation prediction are shown in Fig. 10(d). This figure also includes a plot from the prediction equation from ACI 363 for high-strength concrete, which is given by:

$$E_c = (0.0297\sqrt{f'_c} + 0.0617)(w_c)^{1.5} \tag{2}$$

Fig. 10 demonstrates the effect of various combinations of SF and FA on modulus values. Fig. 10(a–d) show the elastic modulus for all data (except mix L4 in series III which is lightweight concrete) from all series versus the square root of the compressive strength. Fig. 10(a) shows the data plotted for specimens with SF only, Fig. 10(b) shows the data plotted for specimens with FA only, Fig. 10(c) shows the data plotted for all specimens having a combination of SF and FA, and Fig. 10(d) shows the data plotted for all specimens. Also shown on these figures are prediction equations from ACI 318-02 and ACI 363. The graph in Fig. 10(d) shows that ACI 363 has a better prediction modulus values than ACI 318-02. The best-fit curve for this data is very close to the ACI 363 equation. This graph shows that the ACI 363 prediction equation can be used to predict modulus values for HPC with percentages of fly ash and silica fume similar to those used in this study. This is expected since ACI 363 gives better predictions for HSC

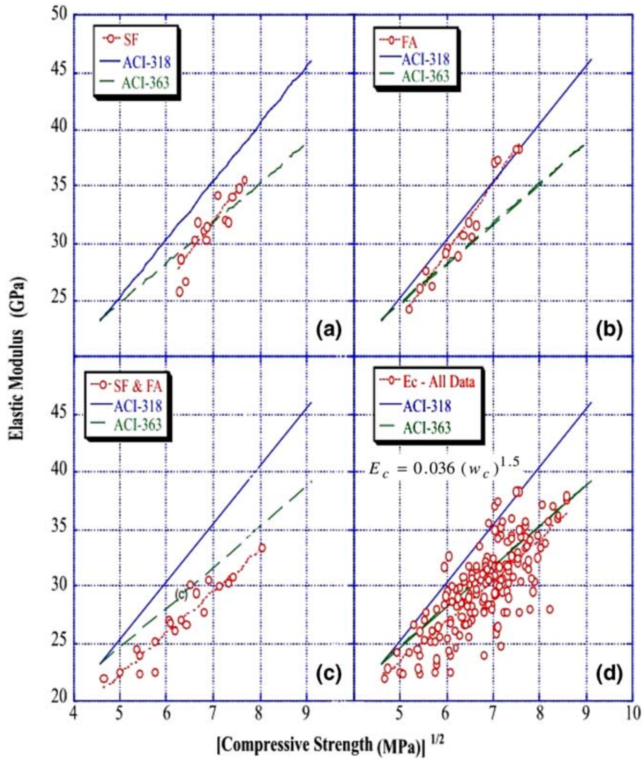

Fig. 10. Comparison of ACI equations and experimental results for the elastic modulus versus concrete strength for series I, II, and III for all data.

and that ACI 318-02 is used for 28-day concretes. However, a simpler form similar to that of ACI 318-02 equation and using a best fit for all data would yield the following equation.

Nassif et al. (2004) has recommended one equation that can be used for HPC that incorporates pozzolanic material as follows:

$$E_c = 0.036(w_c)^{1.5}\sqrt{f'_c} \tag{3}$$

Eq. (3) is a best-fit line equation considering all data except for mix L4 that contains lightweight aggregate and therefore have similar statistical characteristics. Eq. (3) format is used to compare the general trends for the elastic modulus for various combinations of pozzolanic material. Based on data shown in Fig. 10(a–c) and for a value for $w_c = 2400\ \mathrm{kg/m^3}$, the constant in Eq. (3) changes to 4540 for SF only, 4940 for FA only, and 4300 for SF and FA combination.

It is also interesting to note that in Fig. 10(a), where SF was added only, ACI 363 is better than ACI 318-02, while in Fig 10(b) the latter is better than former. It is also observed that in Fig. 10(c) where large amounts of pozzolanic materials are used, both equations, ACI 363 and ACI 318-02, do not accurately predict the elastic modulus. This suggests that there is a need to modify equation ACI 363 to account for pozzolanic material as well. There is also a need for further research to understand the behavior of HPC at the micro-structure level with the presence of SF and FA.

7. Conclusions and recommendations

For normal concrete, the elastic modulus and square root of the compressive strength are proportional and concretes with higher strength will have higher elastic modulus. However, this is only true if the only varying parameter is w/(c + p) ratio. The elastic modulus of HPC is influenced by the constituents of the mix. Based on the results of the experimental investigation of the effect of pozzolan additions and the curing methods on the elastic modulus, the following conclusions are made:

1. The addition of silica fume to HPC seems to reduce the rate of increase of the modulus of elasticity with age. The reason for this is due to the high rate of hydration of concrete containing silica fume. At early age, silica fume concrete has higher strength gain but gradually decreases to ordinary concrete. Hence, the elastic modulus at early age is higher with a gradual decrease over time.
2. At an early age, the percentage gain in modulus is higher than the gain in strength when pozzolans are added to the concrete.
3. The addition of fly ash to HPC increases the elastic modulus over ordinary concrete; however, the rate of change of elastic modulus for fly ash concrete remains the same. On the other hand, when silica fume is added to fly ash concrete, the rate of change of elastic modulus is reduced.
4. The rate of increase of elastic modulus is less than that of compressive strength. The elastic modulus of HPC using granulated blast furnace slag and silica fume increases with age, and the rate of increase becomes less as the concrete approaches 28 days. Moreover, the addition of fly ash to HPC seems to reduce the rate of increase of the modulus of elasticity with age.
5. Specimens cured using wet burlap showed an increase of modulus with age while those cured using dry curing and curing compound showed less increase and sometimes a decrease of modulus. Although the compressive strength of concrete continues to increase with age despite improper curing, this may not be true for the elastic modulus.
6. The ACI 363 equation seems to provide a good prediction of the elastic modulus of HPC using pozzolanic materials. However, for large amounts of fly ash, the prediction is not accurate, and it tends to underestimate the elastic modulus. Moreover, for mixes with a combination of SF and FA, the ACI 363 equation overestimates the elastic modulus values. In comparison, the proposed equation (Eq. (3)) can be

used for HPC with different combination of pozzolanic material.
7. Although the effect of pozzolans on the elastic modulus could still be related to the compressive strength, there is a need to further evaluate their effect on the elastic modulus in terms of their influence on shrinkage, density, and permeability.

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