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Strength properties of high-volume fly ash roller compacted and workable concrete, and influence of curing condition

Cengiz Duran Atiş*

Civil Engineering Department, Çukurova University, 01330, Balcalı-Adana, Turkey

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Abstract

A laboratory investigation was carried out to evaluate the strength properties of high-volume fly ash (HVFA) roller compacted and superplasticised workable concrete cured at moist and dry curing conditions. Concrete mixtures made with 0%, 50% and 70% replacement of normal Portland cement (NPC) with two different low-lime Class F fly ashes, good and low quality, were prepared. Water–cementitious material ratios ranged from 0.28 to 0.43. The compressive, flexural tensile and cylinder splitting tensile strengths were measured and presented. The relationship between the flexural tensile and compressive strengths was discussed. The influence of loss on ignition (LOI) content of fly ash on water demand and the strength of concrete was also discussed. The influence of moist and dry curing conditions on the high-volume fly ash (HVFA) concrete system was assessed through a proposed simple efficiency factor. The study showed that producing high-strength concrete was possible with high-volume fly ash content. LOI content increased the water demand of fresh concrete. HVFA concrete was found to be more vulnerable to dry curing conditions than was NPC concrete. It was concluded that HVFA concrete was an adequate material for both structural and pavement applications.

Keywords: High-volume fly ash; Concrete; Strength; Superplasticizer; Curing; Efficiency factor

1. Introduction

Energy saving, high cost of cement and pressure of environmental lobbyists strengthen the use of by-product cementing materials, such as fly ash, silica fume and rice husk ash to replace cement in concrete.

Currently, blending cement with fly ash, silica fume, slag or a natural pozzolan and using a fly ash in concrete or in roller compacted concrete (RCC) for pavement and dam applications are widespread in practice. The use of fly ash in concrete is both economical and modifies the properties of concrete in both the fresh and hardened states, with improvements to workability, strength, abrasion, heat evolution and shrinkage [1–8]. In addition, the storage and disposal problem of fly ash, which is an industrial waste or by-product, is also solved by the use of fly ash in concrete; otherwise, fly ash has to be disposed of in landfills at a considerable cost [9–12].

On the other hand, the use of superplasticizer is made possible to produce a workable concrete with low water–cement ratio, resulting in higher strength and better durability properties. In general, the use of superplasticizer in concrete results with higher early compressive strength and equal long-term strength compared with concrete containing no superplasticizer. It is believed that higher early strength, which is caused by the use superplasticizer, is a result of a cement dispersing mechanism of the superplasticizer. The cement dispersing mechanism makes available more cement grain surfaces to be accessible for the water, thus, early hydration is more complete [11,13–15]. The use of superplasticizer promoted the use of mineral admixture in concrete,

* Tel.: +90 322 338 6084x27; fax: +90 322 338 6126.
E-mail address: cengiz@cukurova.edu.tr.

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particularly the use of high-volume fly ash (HVFA) in concrete with a low water–cementitious material ratio.

A literature survey on the compressive strength of Class F fly ash concrete and replacement ratio of fly ash with cement has been carried out. This is given in the succeeding discussions.

Mukherjee et al. [16] reported the results of a superplasticised fly ash concrete mixture containing 37% fly ash by weight of total cementitious material (600 kg/cm^3) and a 0.28 water–cemetitious material ratio. They reported 35–37, 51–54, 62–67 and 63–74 MPa cylinder sample compressive strengths at 7 and 28 days, 3 months and 1 year, respectively.

Swamy and Mahmud [17] worked on superplasticised concrete containing 50% low-lime fly ash as cement replacement. The amount of cement was 470 kg/m^3 for a unit volume of a concrete mixture. The water–cementitious material ratio and dosage of superplasticizer were 0.3 and 1.8% of the total cementitious material by mass, respectively. They reported 63- and 53-MPa cube compressive strength at 28 days for moist and dry curing, respectively.

Jiang and Malhotra [18] studied on non-air-entrained concretes containing 55% fly ash as cement replacement by mass. The water–cementitious material ratios ranged from 0.34 to 0.39. The quantity of the cement was 400 kg/m^3 for a unit volume of a concrete mixture. There were reported ranges of the cylinder sample compressive strengths of concrete containing various fly ash, i.e., 18.0–42.2 MPa at 7 days, 30.7–55.8 MPa at 28 days and 43.9–65.2 MPa at 3 months.

Bouzoubaa and Lachemi [19] reported the compressive strength of HVFA self-compacting concrete containing 60% fly ash by weight of total cementitious materials (400 kg/m^3) and water–cementitious material ratio 0.45. The compressive strengths of cylinder samples were 5.2, 15.6 and 30.2 MPa at 1, 7 and 28 days, respectively.

Poon et al. [20] replaced the cement with 45% fly ash by mass and reported 89 MPa at 28 days and 107 MPa at 90 days cube compressive strength of concrete made with 0.24 water–cementitious materials ratio. The concrete reported contains superplasticizer and 640 kg/m^3 cementing material.

Malhotra and his associates replaced the cement with fly ash up to 55–58 mass% [21–27] and utilized various amounts of superplasticizer to maintain the workability. They reported 18, 30 and 42 MPa average cylinder compressive strength at 7 and 28 days and 3 months, respectively. The water–cementitious material ratio of the concrete reported was in the range of 0.33, and contains 370 kg/m^3 cementing materials.

Lam et al. [28] replaced cement with 45% fly ash by mass to evaluate the degree of hydration of a fly ash cement paste. They reported 23.3, 58.9, 95 and 94.9 MPa 28-day compressive strength of fly ash paste made with 0.5, 0.3, 0.24 and 0.19 water–cementitious material ratios, respectively.

Jiang et al. [29] replaced cement with 70% fly ash by mass and reported 26 MPa at 28 days and 36 MPa at 3 months cylinder compressive strength of concrete made with 0.37 water–cementitious material ratio. The concrete reported was containing 333 kg/m^3 cementing material.

Xie et al. [30] replaced cement with 30% fly ash by mass, while they were optimizing the mix parameters of high-strength self-compacting concrete with ultrapulverized fly ash. They reported a 38-MPa compressive strength of concrete at 28 days. The concrete reported was made with 0.38 water–cementitious material ratio and 475 kg/m^3 cementing material.

Yin et al. [31] replaced cement with 53% fly ash while investigating on the compounding and application of C80–C100 high-performance concrete. They reported 37.2- and 95.2-MPa 7- and 28-day cube compressive strengths, respectively, of fly ash concrete made with 0.23 water–cementitious material ratio. The concrete reported was containing 580 kg/m^3 cementing materials.

There were numerous studies on the strength characteristics of concrete containing fly ash. However, there is little study in the literature regarding the strengths of very HVFA concrete (i.e., 70% replacement) with very low and optimal water–cementitious material ratio (i.e., 0.28–0.29). Thus, the aim of this work is to provide more data for the strengths of very HVFA concrete. Another aim of this work is to prove that a high-performance concrete with moderate and high strength could be produced using very high volumes of fly ash as cement replacement (i.e., 70% replacement). These are achieved through designing an RCC (zero slump) concrete and superplasticized-workable concrete containing HVFA for pavements and structural purposes, and measuring their strength properties cured at different relative humidity conditions. Another aim of this study was to assess the influence of the loss on ignition (LOI) contents of fly ash on water demand because it was believed that LOI content increases the water demand of a concrete mixture for a given consistency [15,32,33].

Most of the studies cited in this paper, regarding high-volume fly ash concrete, presented the strength characteristics up to 3 months. A few works presented the results of 6 months and 1 year or more. The current work presents the results of strength characteristics up to 1 year.

Various concrete mixtures with different water–cementitious material ratios were prepared with the inclusion of high volumes of two different fly ashes as cement replacement and a superplasticizer to assess the ashes' influence on the strengths.

In this paper, only strength characteristic results are presented. Other properties of the concrete, made with good-quality fly ash, including abrasion, shrinkage, heat evolution and carbonation, were published elsewhere [6,7,34,35].

The present laboratory measurements were carried out in the laboratory of Civil Engineering Material Unit at Leeds University in England.

2. Materials used in the investigation

2.1. Cement

The cement used was normal Portland cement (NPC), which conforms to the current specifications as described in BS12 [36]. Its chemical and physical properties are given in Table 1. The specific gravity of the cement was 3.15. Its Blaine specific surface area was 3500 cm^2/g.

2.2. Fly ash

The fly ashes used were obtained from the electricity-generating Drax and Aberthaw Power Station in England. Drax and Aberthaw fly ashes are classified as low-calcium Class F fly ash in ASTM-C618 [37] since they are obtained from butimunios coal. The chemical and physical properties of the ashes are given in Table 1. The specific gravity of the Drax and Aberthaw fly ashes were 2.40 and 2.28, respectively. The Blaine specific surface areas were 3100 and 2870 cm^2/g in the same respect.

Some standard specifications, ASTM C-618 [37], BSI 3892 [38] and EN 450 [39], for the chemical and physical properties of a fly ash are given in Table 2.

ASTM [37] requires that a Class F fly ash shall have at least the total of SAF (SiO_2+Al_2O_3+Fe_2O_3) of 70%. Both fly ashes comply with this criterion because the total SAF of the Drax and Aberthaw fly ashes are 92% and 77.6%, respectively.

ASTM [37], BSI [38] and EN [39] restrict the SO_3 content of fly ash 5%, 2.5% and 3.0%, respectively. ASTM [37] and BSI [38] also restrict the MgO content of fly ash 5% and 4%, respectively. Both fly ashes satisfied these requirements.

The remains of the fly ashes on the 45-μm sieve, which is considered an indication of fineness, were 8.50% and 22.50% for Drax and Aberthaw fly ashes, respectively.

Table 1
Oxide composition of cement and fly ash

Oxide	Cement	Drax fly ash	Aberthaw fly ash
SiO_2	20.80	50.20	44.90
Al_2O_3	4.90	28.60	25.20
Fe_2O_3	3.10	13.20	7.50
CaO	63.30	2.60	2.40
MgO	2.40	1.30	1.20
SO_3	3.00	0.60	0.28
K_2O	0.70	2.40	2.90
Na_2O	0.28	1.00	1.00
LOI	0.80	2.80	15.60

Table 2
Limits of standards for the chemical composition and physical properties of fly ash

	ASTM (1992) Class F [36]	BSI (1993) [37]	EN (1994) [38]
Max moisture	3	0.5	–
Max LOI [%]	12	7.0	5.0
Max SO_3 [%]	5	2.5	3.0
Max MgO [%]	5	4.0	–
Max Alkali [%]	1.5	–	–
Min SiO_2 [%]	–	–	–
Min SAF (SiO_2+Al_2O_3+Fe_2O_3) [%]	70	–	–
Max free lime (CaO) [%]	–	–	1.0–2.5
Pozzolanic activity index (PAI) min [%]	75	–	75% at 28 days; 85% at 90 days
Max fineness (remaining on 45 μm sieve) [%]	34	12.5	40
Max expansion [mm]	–	–	10

European standard [39] and ASTM [37] require that the fineness of a fly ash should be no greater than 40% and 34%, respectively. However, BSI [38] restricts this value 12.5%. Drax fly ash satisfied these three standards [37–39]. The Aberthaw fly ash failed BSI [38]; however, it satisfied ASTM [37] and EN [39] because its retention on the 45-μm sieve was 22.5%.

The loss on ignition (LOI) value of fly ash was also restricted by the standards. BSI [38], ASTM [37] and EN [39] restrict the maximum LOI to 7%, 12% and 5%, respectively. Drax fly ash satisfied these restrictions because its LOI value is 2.8%. Aberthaw fly ash failed these criteria with its 15.60% LOI. The Aberthaw fly ash was specially selected so that the effect of LOI could be studied in HVFA concrete. High carbon content is believed to interfere with the hydration reactions, as well as reducing the workability and increasing the water demand when used in concrete [15,32,33].

2.3. Aggregate

The sand and aggregate used were uncrushed-clean, quartzitic, natural aggregate. The sand complied with the requirements of BS812 [40]. The absorption value is 0.1%, and its relative density at the saturated surface dry (SSD) condition is 2.65.

The gravel was 10 mm, maximum nominal size, with a 0.6% absorption value, and its relative density (SSD) was 2.63.

2.4. Superplasticizer

The superplasticizer used was a commercial carboxylic-type high-range water-reducing agent suitable for fly ash concrete.

3. Concrete mixture composition

The proportions of the control NPC concrete mixtures are 1:1.5:3 by mass NPC, sand and gravel, respectively. The approximate quantity of NPC was 400 kg/m^3. High-volume fly ash (HVFA) concrete systems were made using two NPC replacement levels, 50 and 70 mass%. Two fly ashes were used in the study. The mixtures were made with and without a superplasticizer.

The first step in the determination of water content for the control cement and HVFA concretes was to find the optimum water content for maximum compactability using the vibrating slump test described elsewhere [33]. The optimum water content was determined because it was shown that it provided the maximum strength from the mixture [2]. The optimum water contents obtained from the vibrating slump test were then used to produce the control cement and HVFA concrete mixtures with zero slump. These mixtures were made workable by the use of the superplasticizer.

Table 3 presents the composition of the concrete mixtures produced and tested. M0W (workable) and M0Z (zero slump) correspond to control Portland cement concretes. M1, M2, M3 and M4 are HVFA concretes made with Drax fly ash. M5, M6, M7 and M8 are HVFA concretes made with Aberthaw fly ash.

M1, M2, M5 and M6 mixtures are made with 70% fly ash replacement. M3, M4, M7 and M8 mixtures are made with 50% fly ash replacement. The mixtures M0Z, M2, M4, M6 and M8, with zero slump, are called RCC. The mixtures M0W, M1, M3, M5 and M7 contain also superplasticizer. The use of the superplasticizer was very effective. The mixtures containing the superplasticizer were practically flowable. The values from the flow table measurements are given in Table 3. The mixtures were very stable, they did not bleed; their entrapped air content varied from 1% to 2.9%, and final setting times were in the order of 2–5 h.

The concrete specimens were made with vibration until complete compaction was obtained. All the test specimens were demoulded at 1 day and then cured under constant temperature 20 °C and relative humidity conditions of 65% and 100% RH.

4. Results and discussion

4.1. Influence of LOI content of fly ash on the water demand of a mixture

The optimum water content of the mixtures is given in Table 3. When a comparison was made between the M0Z, M2 and M4 mixtures (comparing NPC and Drax fly ash), it can be observed that when 50% of cement was replaced with Drax fly ash, the optimum water content drops from 0.32 to 0.3; furthermore, it drops from 0.32 to 0.29 if the fly ash replacement is 70%. When another comparison was made between the M0Z, M6 and M8 mixtures (comparing NPC and Aberthaw fly ash), it can be observed that when 50% of cement was replaced with Aberthaw fly ash, optimum water content increases from 0.32 to 0.39; furthermore, it increases from 0.32 to 0.40 if the fly ash replacement is 70%. Based on above statements, it can be concluded that Drax fly ash has a capacity to reduce the water demand of a mixture, while Aberthaw fly ash increases it. This is attributed to the high LOI content of Aberthaw fly ash because LOI contents consist of unburned carbon that is generally present in the form of cellular particles larger than 45 μm. It is believed that cellular particles of unburned carbon tend to increase the water demand for a given consistency [15].

4.2. Compressive strength

The results of the compressive strength obtained in this study are from cubes (100 mm a side), according to the procedures described in BS1881 [41].

The compressive strength developments of HVFA concrete system and NPC control concrete are presented in Tables 4 and 5. It can be seen from Tables 4 and 5 that, at 1 day, the M8 mixture made with 50% Aberthaw fly ash replacement attained lower compressive strength than did the corresponding control mixture (M0Z). However, the strength of the M4 mixture made with 50% Drax fly ash is comparable with the strength of corresponding NPC concrete (M0Z) at 1 day.

Table 3
Mixture proportions for a cubic-meter of concrete

	M0W	M0Z	M1	M2	M3	M4	M5	M6	M7	M8
Cement (kg)	400	400	120	120	200	200	120	120	200	200
Fly ash (kg)	–	–	280	280	200	200	280	280	200	200
Sand (kg)	600	600	600	600	600	600	600	600	600	600
Gravel (kg)	1200	1200	1200	1200	1200	1200	1200	1200	1200	1200
Water (l)	136	128	112	116	132	120	172	160	172	156
Optimum W/C ratio	0.32	0.32	0.29	0.29	0.3	0.3	0.40	0.40	0.39	0.39
Actual W/C ratio	0.34	0.32	0.28	0.29	0.33	0.3	0.43	0.40	0.43	0.39
SP (l)	5.6	–	5.6	–	5.6	–	5.6	–	5.6	–
Flow table (mm)	540	0	550	0	600	0	560	0	570	0

Table 4
Compresssive strength (MPa) of concrete cured at 65% RH with 20 °C

Age	M0W	M0Z	M1	M2	M3	M4	M5	M6	M7	M8
1 Day	12.05	33.51	1.76	7.09	5.62	28.25	NA	4.29	3.20	15.73
3 Days	38.41	45.27	16.34	16.64	31.85	35.30	7.98	10.90	20.22	26.14
7 Days	49.27	52.63	24.01	18.60	38.00	48.30	12.29	14.40	25.36	34.30
28 Days	60.75	64.95	33.25	30.55	57.00	66.55	21.10	22.60	36.60	45.85
3 Months	65.03	68.10	40.75	41.10	60.20	79.90	24.21	28.01	42.65	54.55
6 Months	69.13	72.29	42.45	43.00	67.30	81.60	27.50	29.65	49.70	55.65
1 Year	71.00	77.08	45.00	48.05	67.60	83.60	30.7	31.90	53.00	60.20

Furthermore, the M1, M2 and M3, made with Drax fly ash, and M5, M6 and M7, made with Aberthaw fly ash, concrete mixtures had considerably lower strength than did the corresponding control mixtures M0W and M0Z at 1 day of age for dry and moist curing conditions. Nevertheless, they gained enough strength to be demoulded and placed in the appropriate curing environment.

The concretes containing superplasticizer developed lower compressive strength than did their counterpart nonsuperplastised concrete at 1 day (see Tables 4 and 5). This is attributed to the use of large dosage of superplasticizer in concrete, which caused a retardation in hydration. However, the retarding influence of superplasticizer was disappeared at 3 days and beyond.

The compressive strengths of the mixtures (M1–M2 and M5–M6) containing 70% Drax and Aberthaw fly ashes, respectively, were lower than the compressive strength of the corresponding control mixtures (M0W–M0Z) at all ages covering both dry and moist curing conditions.

The compressive strengths of the mixtures (M3–M4) containing 50% Drax fly ash were comparable or higher than the strength of the corresponding control mixtures (M0W–M0Z) at 28 days of age and beyond. However, the compressive strengths of the mixtures (M7–M8) containing 50% Aberthaw fly ash were lower than the strength of the corresponding control mixtures (M0W–M0Z) at 28 days of age and beyond. Nevertheless, some mixtures attained satisfactory moderate strength, while some mixtures attained high strength at 28 days and beyond.

In general, the compressive strengths of concrete containing Drax fly ash was higher than the strength of its counterpart equivalent concretes made with Aberthaw fly ash because the water–cemetitious material ratio of the concrete containing Aberthaw fly ash was higher than the water–cemetitious material ratio of the concrete made with Drax fly ash. This was a direct result of the high LOI content of Aberthaw fly ash that resulted in higher water demand for the mixtures. Moreover, concrete containing 50% fly ash as cement replacement developed higher compressive strength than did the concrete containing 70% fly ash for both Drax and Aberthaw fly ashes.

Based on the above results and discussion, it can be concluded that Aberthaw fly ash can be used in concrete up to 50% replacement of cement, but it is not suitable for very high replacement of cement, such as 70% or more, for producing high-strength concrete. However, it can be safely used for lean concrete application, as well as for concrete subbase application of road construction.

4.3. Flexural tensile strength

When concrete materials are used for the construction of beams and concrete slabs, either for structural purposes or road-paving purposes, they will be subjected to tensile stresses due to bending action. For this case, flexural tensile strength is of utmost significance.

The flexural tensile strength data obtained by testing a $100\times100\times500$ mm prism specimen according to the relevant standards BS1881 [42] are given in Tables 6 and 7.

It can be seen from Tables 6 and 7 that the flexural tensile strengths of the mixtures containing 70% Drax and Aberthaw fly ashes (M1–M2 and M5–M6, respectively) were lower than the strength of the corresponding control mixtures M0W and M0Z at all ages for dry and moist curing. However, the flexural tensile strengths of the mixtures containing 50% Drax (M3–M4) and Aberthaw fly ashes (M7–M8) were comparable or higher than the strength of the control mixtures at 3 days of age and beyond

Table 5
Compresssive strength (MPa) of concrete cured at 100% RH with 20 °C

Age	M0W	M0Z	M1	M2	M3	M4	M5	M6	M7	M8
1 Day	12.05	33.51	1.76	7.09	5.62	28.25	NA	4.29	3.20	15.73
3 Days	40.72	49.44	17.83	19.80	32.75	36.90	7.07	11.05	19.11	26.55
7 Days	51.54	56.27	24.86	20.09	40.75	49.60	12.05	13.50	24.41	35.10
28 Days	62.66	69.12	43.10	34.10	63.50	70.30	19.34	22.94	41.15	49.60
3 Months	76.85	81.54	63.40	48.75	81.60	83.70	30.15	41.80	59.25	66.40
6 Months	78.53	82.40	70.45	59.90	90.50	84.75	44.15	47.05	64.00	72.65
1 Year	80.21	84.72	75.10	65.50	94.35	87.85	50.25	51.20	72.10	77.40

Table 6
Flexural tensile strength (MPa) of concrete cured at 65% RH with 20 °C

Age	M0W	M0Z	M1	M2	M3	M4	M5	M6	M7	M8
1 Day	1.45	3.49	0.96	1.14	1.32	3.78	NA	0.81	0.48	2.12
3 Days	3.50	3.92	2.17	2.36	3.30	4.17	1.45	1.9	2.88	3.38
7 Days	3.84	4.43	2.73	2.77	4.09	5.21	2.15	2.32	3.33	3.90
28 Days	4.92	5.37	3.81	4.60	5.63	6.11	3.62	3.78	4.15	4.88
3 Months	5.91	6.27	4.53	5.07	5.84	6.87	3.66	4.43	4.95	6.05
6 Months	6.10	6.37	4.58	5.37	6.33	7.35	3.76	4.59	5.42	6.27
1 Year	6.40	6.55	4.95	5.31	6.90	8.19	3.93	4.88	5.61	6.38

for dry and moist curing. The mixtures containing 70% Drax fly ash attained comparable flexural tensile strength to the corresponding control concrete at 3 months of age and beyond for both curing.

In general, concretes made with Drax fly ash showed higher flexural tensile strength than did the equivalent concretes made with Aberthaw fly ash. Moreover, concrete containing 50% fly ash as cement replacement developed higher flexural tensile strength than did the concrete containing 70% fly ash for both Drax and Aberthaw fly ashes.

The flexural tensile strength of the concrete under investigation followed a similar trend to compressive strength. As the compressive strength increased, flexural strength also increased, but at a decreasing rate. It was expected that the compressive and tensile strengths of concrete would be closely related. The relation between compressive and flexural tensile strengths is presented after the topic of splitting tensile strength.

Because the British Airport Authority (BAA) limits the flexural strength of 4 MPa at 28 days [43], it can be concluded that M1, M2, M3, M4, M7 and M8 concrete mixtures can be used as airport pavement quality concrete (PQC) because their flexural strengths were found to be in the range of 4–6 MPa for both curing conditions studied. It is found that M5 and M6 concrete mixtures containing 70% Aberthaw fly ash are not useful for PQC; nevertheless, these concrete mixtures can be used in lean concrete application for subbase construction.

4.4. Splitting tensile strength

Tensile splitting strength data taken from cylinder specimen with a height of 300 mm and a diameter of 150 mm are presented in Tables 8 and 9. The test was carried out according to the current specifications [44].

Table 7
Flexural tensile strength (MPa) of concrete cured at 100% RH with 20 °C

Age	M0W	M0Z	M1	M2	M3	M4	M5	M6	M7	M8
1 Days	1.45	3.49	0.96	1.14	1.32	3.78	NA	0.81	0.48	2.12
3 Days	4.35	4.52	2.45	2.63	4.11	4.77	1.24	1.66	2.85	3.35
7 Days	4.72	5.45	3.14	3.09	4.74	5.53	2.03	2.22	3.62	4.52
28 Days	6.58	6.98	4.38	4.92	6.33	6.59	2.70	3.43	4.45	5.01
3 Months	7.22	7.61	5.61	5.76	7.02	7.59	3.84	5.18	5.40	6.86
6 Months	7.67	7.81	6.71	6.28	7.47	7.89	4.77	5.83	6.14	7.19
1 Year	7.86	8.04	6.92	6.35	7.50	8.22	5.23	6.80	6.45	7.43

Table 8
Tensile splitting strength (MPa) of concrete cured at 65% RH with 20 °C

Age	M0W	M0Z	M1	M2	M3	M4	M5	M6	M7	M8
7 Days	2.55	2.96	2.07	1.81	2.92	3.32	1.24	1.47	2.19	2.75
28 Days	3.10	3.48	2.53	2.51	4.06	4.20	1.92	2.10	2.93	3.45

The tensile splitting strengths of test cylinders made from the mixtures containing 70% Drax and Aberthaw fly ashes were lower than the strength of the control NPC mixture at 7 and 28 days. The tensile splitting strengths of mixtures containing 50% Drax fly ash were higher than the strength of the control NPC mixture at 7 and 28 days, while the splitting tensile strengths of the mixtures containing 50% Aberthaw fly ash were comparable with the strength of corresponding NPC concrete for both dry and moist curing.

In general, as seen in compressive and flexural tensile strengths, the concretes made with Drax fly ash showed higher splitting tensile strength than did equivalent concretes made with Aberthaw fly ash. Moreover, concrete containing 50% fly ash as cement replacement developed higher splitting tensile strength than did concrete containing 70% fly ash for both Drax and Aberthaw fly ashes.

Current specifications for bridge and road construction specify that concrete to be used in road construction shall have at least 1.85 MPa splitting tensile strength at 7 days [45]. It can be seen from Tables 8 and 9 that fly ash concretes studied in this work complied with the relevant specification, apart from those M5 and M6 for both dry and moist curing. Nevertheless, M2 mixture can be taken into consideration with regard to relevant specifications.

4.5. Relation between compressive and flexural strengths

The compressive strength data and corresponding flexural tensile strength of fly ash concrete, regardless of fly ashes and curing conditions, are represented in Fig. 1. A power relation was established for the current results. The relation obtained was compared with the relevant literature, i.e., Ahmad and Shah [46], ACI 1992 [47], ACI 1995 [48] and TS500 [49], which are also represented in Fig. 1.

In the current analysis, the cube compressive strengths have been converted into cylinder compressive strength by multiplying the cube compressive strength with 0.85 because the regarding literature for the relation between flexural tensile and compressive strengths is mainly based

Table 9
Tensile splitting strength (MPa) of concrete cured at 100% RH with 20 °C

Age	M0W	M0Z	M1	M2	M3	M4	M5	M6	M7	M8
7 Days	2.73	3.26	2.03	1.95	3.37	3.48	1.30	1.40	2.23	2.65
28 Days	3.61	3.94	2.88	2.82	4.46	4.59	1.82	2.04	3.19	3.69

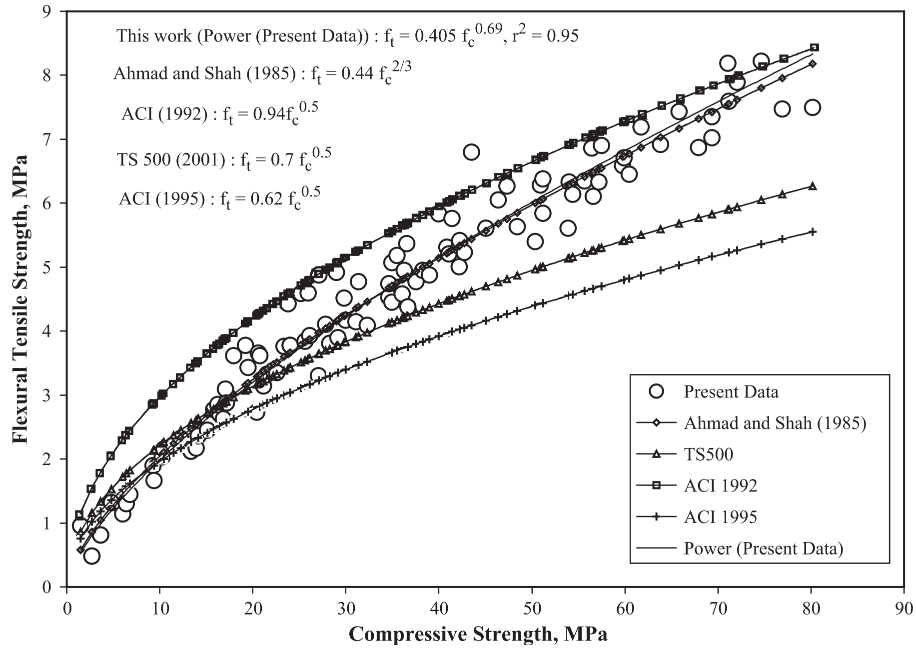

Fig. 1. The relation between flexural tensile and compressive strengths.

on cylinder specimen, "with a height that is twice the size of its diameter", compressive strength.

Fig. 1 shows that the equation of ACI 1992 [47] highly overestimates the flexural tensile strength from its compressive strength data when the compressive strength is lower than 40 MPa; however, it gives a reasonable estimate when the compressive strength is higher than 40 MPa. The equation proposed by ACI 1995 [48] and TS500 [49] underestimates the flexural tensile strength from the compressive strength, and this underestimation is higher for higher-strength concrete (Fig. 1). Ahmad and Shah [46] and current relation give a better and conservative estimate of flexural tensile strength from compressive strength. It can be seen in Fig. 1 that current relation almost coincides with the relation proposed by Ahmad and Shah [46]. Rashid et al. [50], who studied the correlations between mechanical properties of high-strength concrete, gave similar conclusion for the equations given by ACI 1992 [47], ACI 1995 [48] and Ahmad and Shah [46].

4.6. Influence of curing conditions and efficiency factor of fly ash

The influence of curing conditions on the compressive strength of HVFA concrete system was evaluated through a simple efficiency factor proposed in this study. The proposed simple efficiency factor is described as in the following. It is based on the normalization of the compressive strength with the quantity of cementitious materials. The normalization of compressive strength of NPC concrete with the quantity of cement is assumed to be equal to the normalization of the compressive strength of fly ash concrete with its total cementitious materials content treated with efficiency factor $((c-fa)+kfa)$ at a specific age (see Eq. (1)). Here, it is assumed that the curing condition and water–cementitious ratio of the corresponding mixtures are equal or similar (i.e., optimal).

$$\frac{f_c(t)_{\mathrm{npc}}}{c} = \frac{f_c(t)_{\mathrm{fa}}}{(c-fa)+kfa} \tag{1}$$

From Eq. (1), the efficiency factor (k) of fly ash can be written as follows (Eq. (2)),

$$k = \frac{c}{\mathrm{fa}}\left(\frac{f_c(t)_{\mathrm{fa}}}{f_c(t)_{\mathrm{npc}}} - 1\right) + 1 \tag{2}$$

The c/fa means the inverse of the fly ash replacement ratio (r_{fa}). When this value is substituted into Eq. (2), then Eq. (3) is obtained.

$$k = \frac{\left(\frac{f_c(t)_{\mathrm{fa}}}{f_c(t)_{\mathrm{npc}}} - 1\right)}{r_{\mathrm{fa}}} + 1 \tag{3}$$

where, k is the efficiency factor of fly ash, c is the quantity of total cementitious material(s), fa is the quantity of fly ash, r_{fa} is the replacement ratio of fly ash (i.e., 0.3 for 30%, 0.5 for 50% and 0.7 for 70% replacement), $f_c(t)_{\mathrm{npc}}$ is the compressive strength of NPC concrete at time t, $f_c(t)_{\mathrm{fa}}$: compressive strength of FA concrete at time t.

Based on the above equations and compressive strengths, the efficiency factors of the fly ashes used in this study were calculated according to its counterpart NPC concrete mixtures through curing time. The results are presented in graphical form in Fig. 2 (a–h).

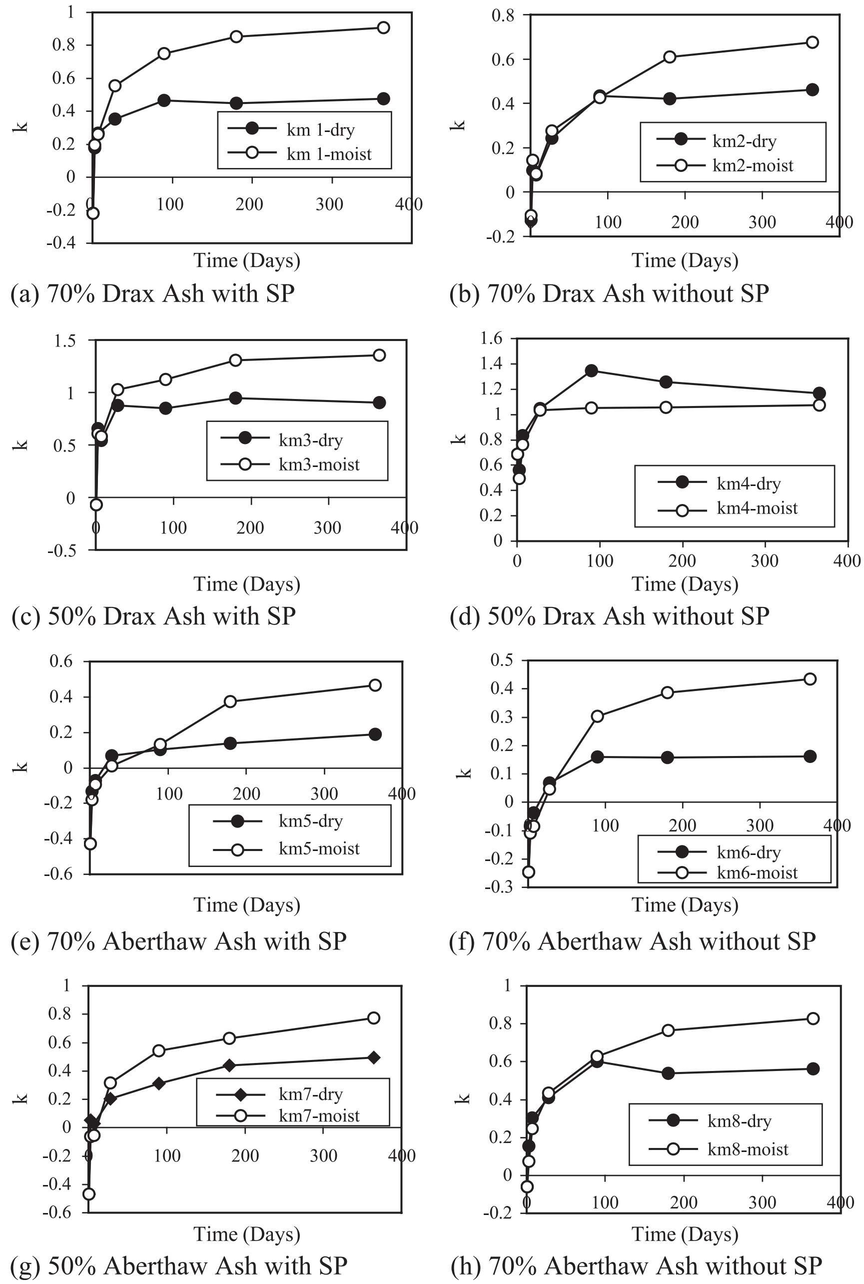

Fig. 2. Influence of curing conditions and time on development of efficiency factor of fly ash concrete. (a) 70% Drax Ash with SP; (b) 70% Drax Ash without SP; (c) 50% Drax Ash with SP; (d) 50% Drax Ash without SP; (e) 70% Aberthaw Ash with SP; (f) 70% Aberthaw Ash without SP; (g) 50% Aberthaw Ash with SP; and (h) 70% Aberthaw Ash without SP.

It can be seen from Fig. 2 (a and b) that the efficiency factor of HVFA concrete made with Drax fly ash and 70% mass replacement is negative at a very early age. It can be considered a constant (0.4) after 3 months of dry curing conditions. However, it changes for moist curing conditions and doubles up when compared with dry curing conditions, until 1 year of age. Fig. 2 (c) shows that the efficiency factor of HVFA concrete made with Drax fly ash and 50 mass% replacement is almost 1 at 28 days for moist and dry curing. The development of efficiency factor continues in moist curing conditions beyond 28 days, while it can be considered a constant about 1 for dry curing conditions. The efficiency factor is about 1.4 for moist-curing conditions at 6 months of age, which means Drax fly ash is more efficient than the cement itself. Fig. 2 (d) showed contradictory results, which was attributed to the variation.

It can be seen from Fig. 2 (e and f) that the efficiency factor of HVFA concrete made with Aberthaw fly ash and 70% mass replacement is negative at an early age and very small at 28 days and beyond for dry curing conditions. Although it improves in time for moist curing condition, it is smaller when compared with the efficiency factor of Drax fly ash. It can be considered a constant (0.1–0.2) after 28 days for dry curing conditions. However, it changes for moist curing conditions, it seems to increase three times until 1 year of age when compared with dry curing condition.

Fig. 2 (g and h) shows that the efficiency factor of HVFA concrete made with Aberthaw fly ash and 50% mass replacement is about 0.3 at 28 days for moist and dry curing. Development of efficiency factor continues in moist curing conditions beyond 28 days. The efficiency factor is about 0.8 for moist curing conditions at 1 year of age, while it can be considered a constant of 0.4–0.5 for dry curing.

Fig. 2 (a and h) shows how the curing conditions influence the long-term compressive strength of HVFA system through the efficiency factor. Fig. 2 (a–h) proved that the efficiency factor of fly ash concrete is not only dependent on curing time but also on the replacement level and relative humidity.

In addition, it can be seen from a close observation of Fig. 2 (a–h) that the vulnerability of the HVFA concrete system to dry curing condition becomes more marked with the higher replacement of fly ash. This conclusion is in agreement with the published results [51,52].

Although, there are studies conducted with fly ash concrete, this work provides strength characteristics of very high-volume fly ash concrete made with and without superplasticizer and cured at moist and dry curing environments with 20 °C up to 1 year of age. This work proved that a nonstandard fly ash (i.e., Aberthaw fly ash) can be used as a cement replacement in concrete. In addition, it was shown that the influence of curing conditions on fly ash concrete may be assessed with a simple efficiency factor.

5. Conclusions

From the laboratory results that used Class F type of fly ash, the following conclusions are made:

1. The study proved that it is possible to convert an RCC (zero slump) concrete to a workable concrete with the use of a suitable superplasticizer.
2. A simple efficiency factor is proposed through which the influence of curing conditions on HVFA system can be observed. The study showed that the efficiency factor is not a constant but depends on different parameters, including curing conditions, curing time and fly ash replacement ratio.
3. Drax fly ash had a capacity to reduce the water demand of a concrete mixture, while Aberthaw fly ash increased it due to its high LOI content. This resulted that concrete containing Drax fly ash developed higher strength than that of its counterpart Aberthaw fly ash.
4. The concretes containing superplasticizer developed lower compressive strength than did their counterpart nonsuperplastised concrete at 1 day. However, the influence of superplasticizer disappeared at 3 days and beyond.
5. HVFA concrete attained satisfactory or higher compressive and tensile strengths when compared with NPC concrete.
6. The concrete containing 50% Drax fly ash developed high strength, while 70% fly ash replacement concrete developed moderate strength. The concrete containing 50% Aberthaw fly ash developed satisfactory strength at 28 days and high strength at 1 year.
7. HVFA concrete was found to be more vulnerable to dry curing conditions than that of NPC concrete.
8. With its high strength properties, HVFA roller compacted concrete becomes a possible alternative to NPC concrete used for road pavements applications and large industrial floors.

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