

Center for By-Products Utilization

EXPERIMENTAL INVESTIGATION ON WATER- TO-CEMENTITIOUS MATERIALS RATIO OF CEMENT MORTAR CONTAINING FLY ASH

By Tarun R. Naik and Rakesh Kumar

Report No. CBU-2001-20
REP-444
October 2001

Submitted for publication in Cement and Concrete Research

**Department of Civil Engineering and Mechanics
College of Engineering and Applied Science
THE UNIVERSITY OF WISCONSIN - MILWAUKEE**

**EXPERIMENTAL INVESTIGATION ON WATER-TO-CEMENTITIOUS
MATERIALS RATIO OF CEMENT MORTAR CONTAINING FLY ASH**

Tarun R. Naik^{a,*} and Rakesh Kumar^b

*^aDirector, UWM Center for By-Products Utilization, Department of Civil Engineering and Mechanics,
College of Engineering and Applied Science, W309 EMS Building, P.O. Box 784, Milwaukee, WI
5320, USA*

^bResearch Associate, UWM Center for By-Products Utilization, Milwaukee, USA

* Corresponding author. Tel: 1-414-229-4105; Fax: 1- 414-229-6958. E-mail address: tarun@uwm.edu

EXPERIMENTAL INVESTIGATION ON WATER-TO-CEMENTITIOUS MATERIALS RATIO OF CEMENT MORTAR CONTAINING FLY ASH

Abstract

The study focuses on the applicability of Abram's law for the cement mortar containing fly ash as a cement replacement. ASTM Class C and Class F fly ashes were used to replace cement in the range of 20% to 40% by weight of cement. The water to cementitious material ratio of the mortars under study was varied from 0.27 to 4.97. The application of the Abram's law concludes that use of ASTM Class C fly ash and Class F fly ash reduces the optimum water to cementitious material ratio in comparison of water to cement ratio of the neat paste. The optimum water to cementitious material ratio (by weight) for Class C fly ash and Class F fly ash was found to range between 0.35 to 0.6. The study further presents a relationship for converting water-to-cementitious materials ratio by weight to water-to-cementitious materials ratio by volume.

Keywords: Cement replacement; Cement mortar; Fly ash; Water-to-cementitious ratio; Strength

1. Introduction

It is beyond dispute that the most important factor affecting the compressive strength of cement-based composites i.e. cement paste, mortar, and concrete, etc. is water to cement ratio [1-3]. In recent decades, various types of supplementary cementitious materials or pozzolanic materials such as fly ash, silica fume, ground granulated blast furnace slag, used foundry sand, etc. are being incorporated for the partial replacement of cement [1,4-6]. Pozzolanic material is different from portland cement mainly in three aspects namely: specific density, particle size and pozzolanic activities. Fly ash usually finer than cement, affects properties of concrete due to its filling as well as pozzolanic effects [4]. In fresh paste, mortar etc. the mixing water may be broadly divided into two parts. One is filling water, which fills the voids between the particles and does not contribute to the fluidity of paste. The other part is the water in surface layer, which forms water film on the particle surface. The fluidity of paste depends on the thickness of water film [7]. The addition of pozzolanic material affects filling water and amount of the water in surface layer. Filling water is related to packing density of the system while the amount of water in surface layer is related to specific surface of the material. For the cement containing pozzolan, the maximum and the minimum ratio of water to cement is related to the specific surface and content of pozzolan [7].

Previous research has shown that the addition of fly ash to concrete mixtures reduces water requirement for a given workability [8-11]. The decrease in water demand has been attributed to ball bearing effects of spherical particles of fly ash in the mixtures.

Helmuth [12] reviewed critically the water-reducing properties of fly ash in cement pastes, mortars, and concrete. He reported that the reduction in water-

requirement in the mixtures containing fly ash might not be because of ball bearing effects of spherical fly ash particles as generally described in the literature but it might be primarily due to absorption of very fine fly ash particles on cement particles surfaces which in turn causes dispersion of the cement particles similar to that obtained through addition of organic water-reducing admixtures.

There is very little information available in literature on applicability of Abram's law for cement mortar containing fly ash. In this experimental investigation, an effort has been made to understand the applicability of Abram's law for cement mortar containing fly ash as cement replacement.

Abram's law states: "For a given cement and conventional aggregates in workable mixtures, under similar conditions of placement, curing, and test the strength of concrete is solely a function of the ratio of free water to cement in the plastic mixture mathematically expressed as given below;

$$f_c = A/B^{w/c}$$

Where c = compressive strength of concrete

w/c = water/cement ratio of the concrete mixture

A and B are constant at a given most curing age [13]. For concrete containing supplementary cementitious and/or pozzolanic materials such as fly ash, silica fume, granulated blast furnace slag etc., as partial replacement of cement, the Abram's law of water to cement ratio is not directly applicable [13].

2. Experimental program

2.1 Materials

2.1.1. Cement

ASTM C 140 [14] Type I, normal portland cement was used throughout this investigation.

2.1.2. Fly ash

Class C and Class F fly ashes conforming to ASTM C 618 requirements were used for this study.

2.1.3 Fine aggregate

Natural sand obtained from a local ready-mix concrete producer was used as fine aggregate.

2.1.4 Water

Potable tap water available in the Center for By-Products Utilization laboratory was used for mixing mortar mixtures.

2.2 Proportioning of mortar mixtures

For this experimental study, four series of cement mortar mixture namely Mixture A through Mixture D as given in Table 1 were proportioned with varying water-to-cementitious materials ratio. Mixture A is control mixture with cement to sand ratio of 1:275. The water-to-cementitious materials ratio of this series of mixtures was varied

from 0.27 to 4.97. Mixtures B contained 20% replacement of cement by weight by Class C fly ash while the mixture C and D contained 20% and 40% replacement of cement by Class F fly ash respectively. The water-to-cementitious materials ratio of these mixtures was varied from 0.27 to 0.78, 0.27 to 4.97, and 0.27 to 4.97 respectively. Table 2 through Table 5 present the water-to-cementitious materials ratio of various mixtures.

2.3. Preparation and testing of cube specimens

For each mixture proportions, 2-inch mortar cubes were cast and moist-cured for 24 hours. The specimens were demolded after 24 hours of casting and immersed in lime-saturated water until the time of testing. All the cubes were tested for strength in compression at 7 and 28 days of age in accordance with the relevant ASTM standard.

3. Results and discussion

The test results are presented in Table 2 through Table 5 and also in figures 1 through 4. It is obvious from the test results that compressive strength of mortar increases with increase in water to cementitious material ratio up to a certain level i.e. optimum level. Beyond the optimum value of water to cementitious ratio, strength of mortar decreases and finally becomes almost constant. This reason behind the fact is that below the optimum value of water cementitious ratio, insufficient amount of water is available for completion of hydration reaction for all the cement particles. Further, because of low fluidity of the mortar mixture, “harshness” of mixture compaction might be inadequate to achieve the potential strength. Moreover, beyond the optimum value of water to cementitious ratio strength decreases due to increase in volume of capillary

pores of the mixture due to the increased water content [15-16]. The results presented in Fig. 1 for Mixture A indicate that the optimum water-to-cementitious materials ratio for this series of mixture is 0.57. Since, at this water-to-cementitious materials ratio the mortar attained the maximum compressive strength at the both ages of 7 day and 28 day. Above 0.57 water-to-cementitious ratio, strength of mortar rapidly decreases and beyond 2.47 strength of mortar becomes almost constant.

Fig.2 depicts the compressive strength data of mortar Mixture B containing Class C fly ash at 20% cement replacement. This series of mortar mixture attained higher strength than the control one. The optimum water-to-cementitious materials ratio is lower i.e. 0.37 for this series of mixture than that of control mixture i.e. 0.57. Compressive strength results for mortar with 20% of cement replaced by weight of Class F fly ash are depicted in Fig. 3. It is evident from the figure that the optimum water to cementitious materials ratio for this series of mortar is 0.57. This series of mixture attained about 20% less strength than the control mixture at both ages of 7 days and 28 days.

Results for mixture series D presented in Fig. 4 shows that the optimum water-to-cementitious materials ratio for this mortar series is 0.47. This series of mixtures attained minimum compressive strength than other mixtures including the control mixture. This also indicates that increase in the percent replacement of cement from 20% to 40% by Class F fly ash not only reduces the strength of mortar but also reduces the water to cementitious materials ratio in comparison to that of for 20% replacement of cement. Further, based on the strength data of mortar mixtures containing Class F fly ash it is

obvious that slower pozzolanic reaction of this fly ash is responsible for low strength development.

The use of Class C fly ash has encouraging affect on the strength gain and reduction of water to cementitious ratio. Better cementitious and pozzolanic activity in comparison to Class F fly ash is responsible for this. The higher pozzolanic activity in case of Class C fly ash is associated with its improved fineness and higher lime content. This experimental study reveals that optimum water-to-cementitious materials ratio by weight for the mortar containing fly ash lies between 0.35 to 0.60.

RELATIONSHIP BETWEEN WATER TO CEMENTITIOUS RATIO BY WEIGHT AND WATER TO CEMENTITIOUS RATIO BY VOLUME

The water to cementitious ratio by weight mathematically can be expressed as:

$$R_w = \frac{W_w}{W_{Cm}} \quad \mathbf{1}$$

$$R_w = \frac{W_w}{(W_c + W_{FA})} \quad \mathbf{2}$$

$$R_w = \frac{W_w}{W_{CM} \left[\left(1 - \frac{P}{100} \right) + \frac{P * RR}{100} \right]} \quad \mathbf{3}$$

Where

R_w = Water to cementitious ratio by weight

W_w = Weight of water

W_{cm} = Weight of total cementitious materials (cement and fly ash)

W_{FA} = Weight of fly ash

P = Percent cement replacement by fly ash

RR = Replacement ratio, ratio of fly ash to cement replacement used

The water to cementitious materials ratio by volume can be expressed as

$$R_v = \frac{V_w}{V_c + V_{FA}} \quad 4$$

$$R_v = \frac{W_w}{W_{cm}} \left[\frac{1}{\frac{(1-P)}{S_c} + \frac{P * RR}{S_{FA}}} \right] \quad 5$$

$$R_v = \frac{\frac{W_w}{r_w}}{\left[\frac{(1-P)}{r_c} W_{cm} + \frac{P W_{cm} RR}{r_{FA}} \right]} \quad 6$$

$$R_v = R_w \times CF \quad 7$$

Where

R_v = Water to cementitious materials ratio by volume

\tilde{n}_w = Density of water

\tilde{n}_c = Density of cement

\tilde{n}_{FA} = Density of fly ash

S_c = Specific gravity of cement

S_{FA} = Specific gravity of fly ash

CF = Conversion factor, and it is given by the following relation:

$$CF = \frac{I}{\left[\left(\frac{I-P}{S_C} \right) + \frac{P*RR}{S_{FA}} \right]}$$

8

The values of CF can be multiplied by water-to-cementitious materials ratio by weight in order to obtain the water to cementitious materials ratio by volume (Eq. 7). The CF factor is a function of amount of cement replacement by fly ash, replacement ratio (RR), specific gravity of cement and fly ash.

Equation 8 gives general conversion factor (CF) for converting water to cementitious ratio by volume. When the replacement ratio (RR) is zero, then R_w and R_v becomes W/Cm by weight and W/Cm by volume, respectively for mixtures containing fly ash. For mixtures without fly ash, both P and RR become zero for obtaining the desired water to cement ratio. The computed values of CF are presented in Table 6 for the present study.

The general trend of the results remains the same as described above for the weight ratio (R_w) when water to cementitious ratio is expressed by volume (R_v). However, the strength values will be represented at higher water to cementitious ratio by volume relative to water to cementitious ratio by weight as determined by the factor CF. Compressive strength data for mixes tested are plotted as a function of water-to-cementitious ratio on both weight and volume basis (Figure 1 through 4).

3. Conclusions

This experimental investigation emerges in the following main conclusions

1. Replacement of cement by ASTM Class C fly ash in mortar reduces water to cementitious material ratio more effectively than the ASTM Class F fly ash.

2. The optimum water to cementitious material ratio by weight for mortar containing cement replaced by ASTM fly ash varies between 0.35 to 0.60.
3. Expression of water to cementitious materials ratio by volume does not affect the trend of results obtained based on the same expressed on the basis of weight. However, the strength is represented at a higher value to cementitious ratio when expressed on volume basis than weight basis.

References

- [1] A. M. Neville, Properties of Concrete, fourth ed., ELBS and Longman, 1996.
- [2] T. S. Nagraj, Z. Banu, Generalization of Abram's law, Cem. Concr. Res. 26(6), (1996) 933-942.
- [3] G. A. Rao, Generalization of Abram's law for cement mortars, Cem. Concr. Res. 31(3), (2001) 495-502
- [4] K. Wesche, Fly ash in Concrete's properties and performance, Report of technical committee 67-FAB, use of fly ash in building, EXSPON, London, 1996.
- [5] V. M. Malhotra and A.A. Ramezani-pour, Fly ash in concrete, second ed, CANMET, Canada, 1994.
- [6] P. K. Mehta, Concrete: structure, properties and materials, Prentice-Hall, New Jersey, 1985.
- [7] Z. Chengzhi, W. Aiqin, T. Mingshu, and L. Xjaoyu, The filling role of pozzolanic material, Cem. Concr. Res. 26 (6), (1996) 943-947
- [8] E. E. Berry and V. M. Malhotra, Fly ash for use in concrete – A Critical Review,” ACI Materials Journals, Vol. 77, No. 2, March/April, 1980 pp. 59-73.

- [9] T. R. Naik and B. W. Ramme, High-Strength Concrete Containing Large Quantities of Fly Ash, *ACI Materials Journal*, Vol.86, No. 2 March/April – 1989, pp. 111-116.
- [10] E. E. Berry, R. T. Hemmings, W. S. Langley, and G. G. Carette, Beneficiated Fly Ash: Hydration, Microstructures, and strength development in Portland Cement systems, in *Fly Ash, Silica fume, Slag, and Natural Pozzolans in Concrete*, V.M. Molhotra, Ed., Proceedings of the Third International conference., Trondheim, Norway June 1989. pp. 241-272
- [11] T. R. Naik and B. W. Ramme, Effects of High-Lime fly Ash Content on Water Demand, Workability, Time of set and compressive strength of Concrete,” *ACI Materials Journal*, Vol. 87, No. 6, Nov./Dec. 1990, pp. 619-626.
- [12] R. A. Helmuth, Water-Reducing Properties of Fly Ash in Cement Pastes, Mortars and Concretes: Causes and test methods, in “Fly Ash, Silica fume, slag and Natural Pozzolans in concrete,” V.M. Malhotra, Ed., Proceeding of the Second International Conference, Madrid, Spain, Vol. 1 April 1986, pp. 723-740.
- [13] A. O. Francis, Fly ash concrete mix design and the water-cement ratio Law, *ACI Materials Journal*, Vol. 91, No. 4, July-August 1994, pp. 362-371.
- [14] Annual Book of ASTM Standards, Vol. 04-01, pp. 140-147, 1999.
- [15] Neville, A. M. and Brooks, J. J., “Concrete Technology”, ELBS edition, Logman Singapore, Publishers (Pte) Ltd., 1990.
- [16] Soroka, I., “Portland Cement Paste and Concrete”, McMillan Press Limited, Great Britain, 1979.

Table 1
Mixture designation and description

Mixture Designation	Mixture description
Mixture A	Without fly ash
Mixture B	With 20% ASTM Class C fly ash
Mixture C	With 20% ASTM Class C fly ash
Mixture D	With 20% ASTM Class C fly ash

Table 2

Water-to-cementitious materials ratio and compressive strength of mortar Mixture A

Water/Cementitious materials	Compressive Strength, (MPa)	
	7-day	28-day
0.27	3.4	5.2
0.32	9.3	12.0
0.37	15.2	22.7
0.47	22.6	29.8
0.57	24.0	32.7
0.67	18.1	27.6
0.77	16.6	25.2
0.87	10.7	18.0
0.97	10.7	17.1
1.22	6.2	12.6
1.47	4.8	12.9
1.72	3.7	10.0
1.97	2.5	5.8
2.47	1.5	3.7
2.97	1.6	3.2
3.97	2.3	2.7
4.97	NA	3.1

Table 3

Water-to-cementitious materials ratio and compressive strength of mortar Mixture B

Water/Cementitious materials	Compressive Strength, (MPa)	
	7-day	28-day
0.27	6.7	7.9
0.32	24.4	30.4
0.37	30.1	36.4
0.47	25.6	33.6
0.57	21.7	32.2
0.67	18.0	28.7
0.78	12.3	19.8

Table 4

Water-to-cementitious materials ratio and compressive strength of mortar Mixture C

Water/Cementitious materials	Compressive Strength, (MPa)	
	7-day	28-day
0.27	2.7	3.3
0.32	6.7	7.3
0.37	13.5	17.0
0.47	18.4	23.1
0.57	20.2	27.7
0.67	13.6	19.9
0.77	11.6	16.5
0.87	7.8	15.1
0.97	8.6	11.4
1.22	4.7	9.1
1.47	3.7	6.4
1.72	2.9	5.3
1.97	1.7	3.8
2.47	1.4	2.5
2.97	1.0	1.7
3.97	0.7	1.7
4.97	0.4	0.5

Table 5

Water-to-cementitious materials ratio and compressive strength of mortar Mixture D

Water/Cementitious materials	Compressive Strength, (MPa)	
	7-day	28-day
0.27	2.9	4.0
0.32	4.8	7.2
0.37	12.2	18.6
0.47	13.5	23.6
0.57	12.5	21.0
0.67	9.8	13.6
0.77	8.8	13.9
0.87	6.9	9.7
0.97	5.5	9.7
1.22	4.1	6.7
1.47	2.0	4.1
1.72	2.2	3.9
1.97	1.9	3.5
2.47	0.7	1.9
2.97	0.7	2.2
3.97	0.6	1.4
4.97	0.3	0.8

Table 6

Conversion factor for converting water-to-cementitious material ratio by weight to Water-to-cementitious material ratio by volume

Mixture Number	Conversion factor (CF)*
Mixture A	3.15
Mixture B	3.00
Mixture C	2.94
Mixture D	2.76

*The specific gravity of cement, Class C fly ash, and Class F fly ash was taken as 3.15, 2.52, and 2.32, respectively.

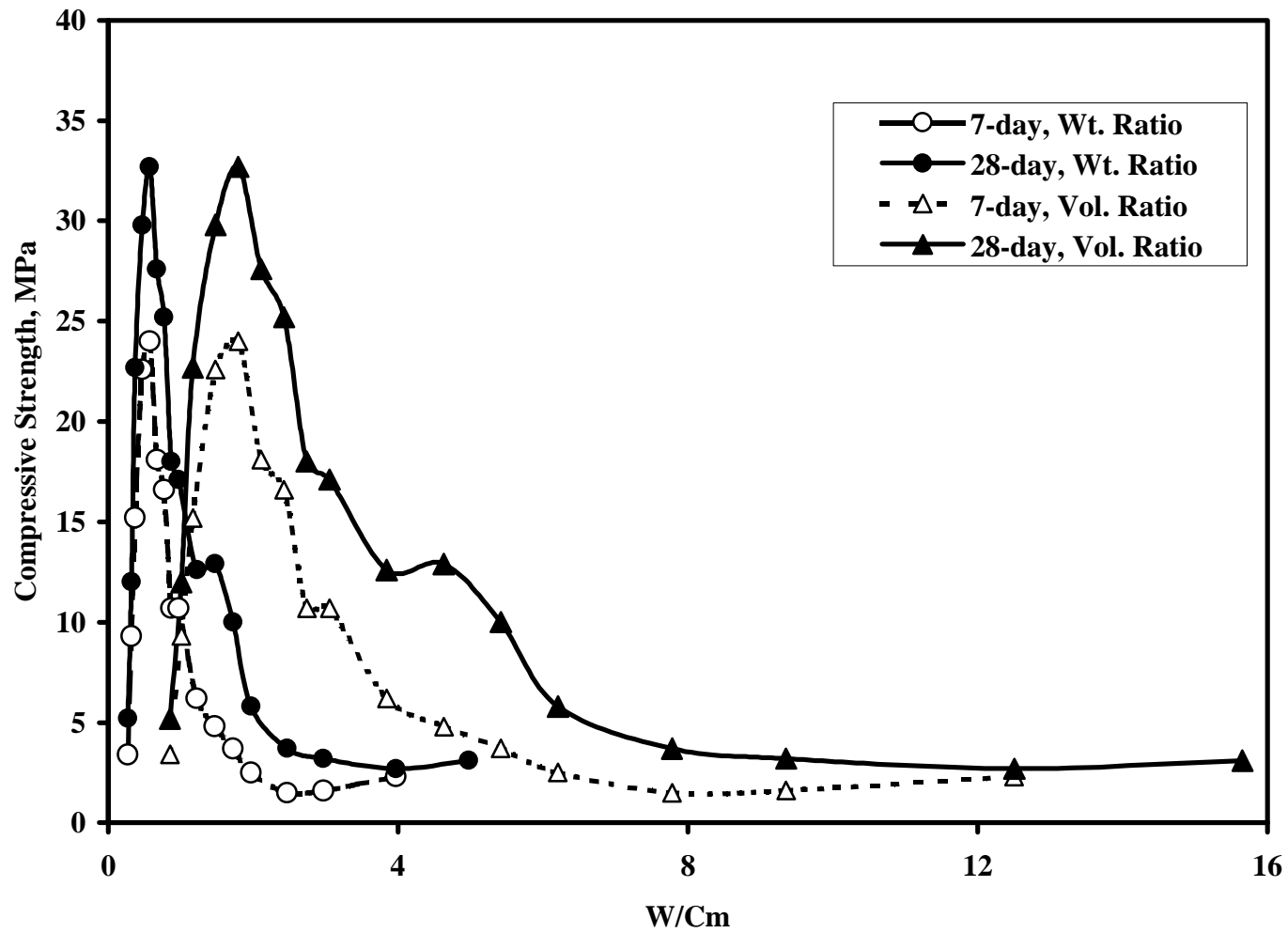


Fig. 1. Compressive strength vs water-to-cementitious material ratio by weight and volume for Mixture A

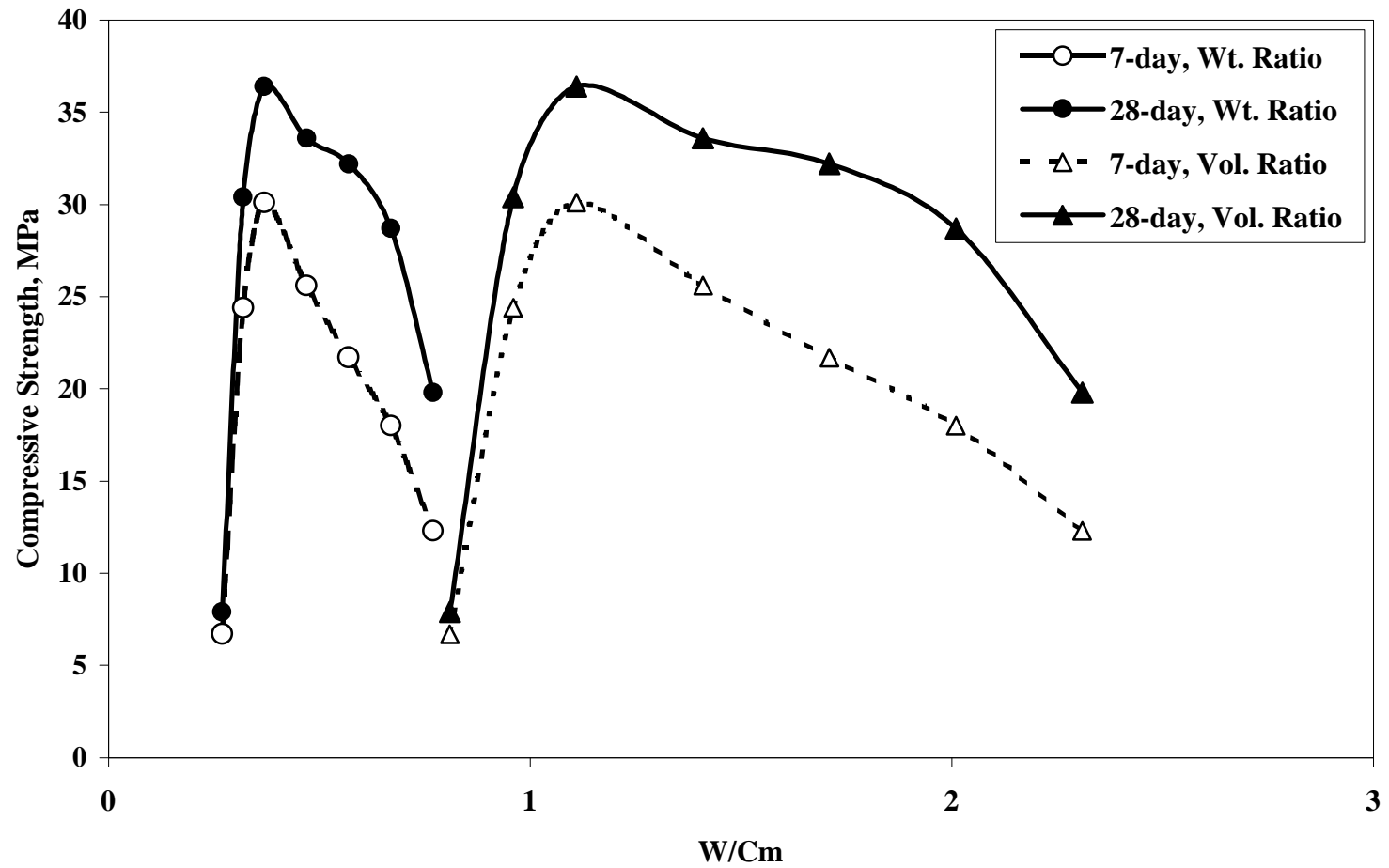


Fig. 2. Compressive strength vs water-to-cementitious ratio by weight and volume for Mixture B

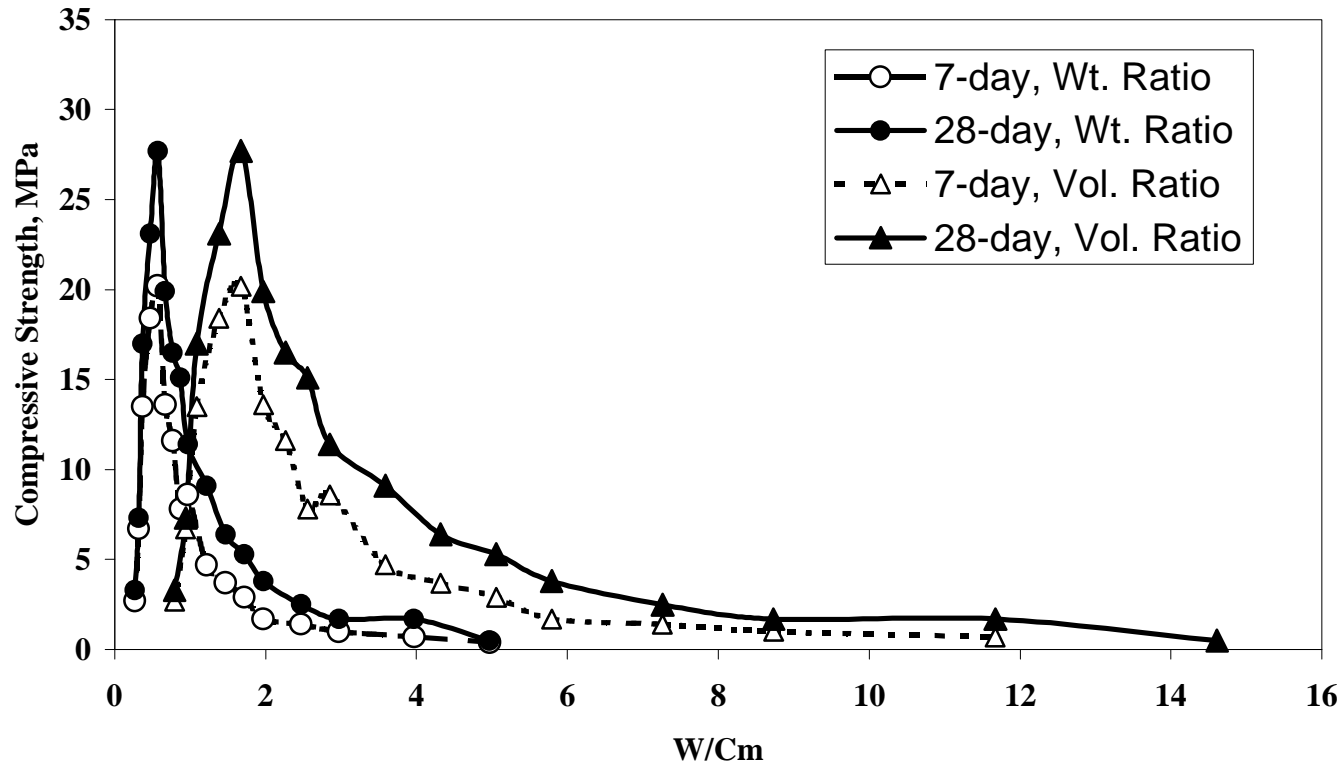


Fig. 3. Compressive strength vs water-to-cementitious materials ratio by weight and volume for Mixture C

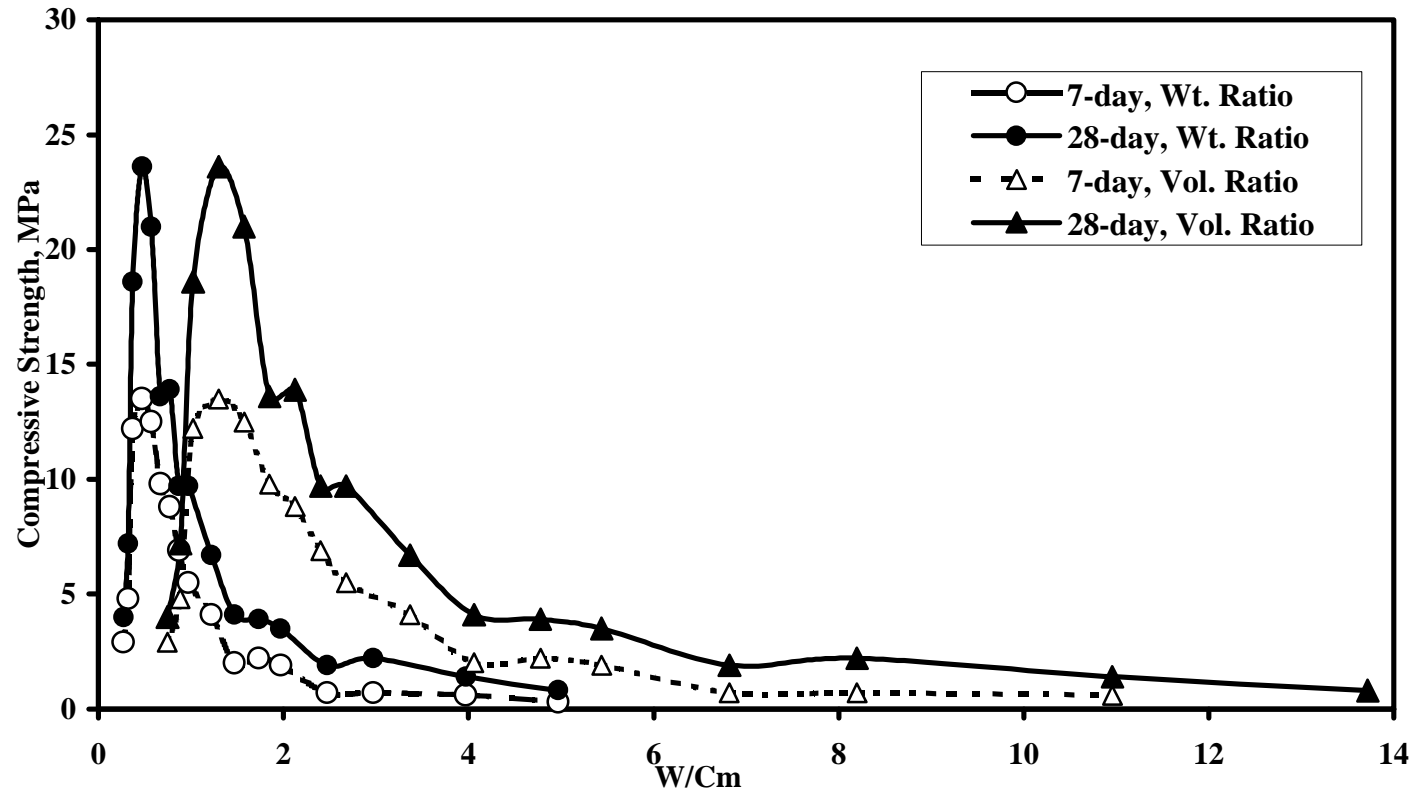


Fig. 4. Compressive strength vs water-to-cementitious material ratio by weight and volume for Mixture D