Characterizing the Short-term Compressive Stress-Strain Behavior and Strength of Cement Grouts Up to Twenty Eight Days using Vipulanandan Stress-Strain Model

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ABSTRACT

Since the durability and quantification of the property changes with time are some of the important issues, in this study compressive stress-strain behavior and strength of cement grouts (Portland cement -Type 1) with and without 10% clay additive with the varying water-to-cement ratio (w/c) up to 1.0 was investigated for up to 28 days. Increasing the w/c ratio increased the initial and final setting times of the grouts. Also the addition of clay reduced the initial and final setting times of the grouts. Compressive stress-strain relationship highlighted the changes in the nonlinear behavior, modulus (initial, secant and tangent), failure strain and strength of the grouts. The addition of 10% clay also increased the compressive strength and the initial tangent modulus by over 80% and 90% respectively after 28 days of curing. The highest compressive strength was for the cement grout with w/c ratio of 0.6 and 10% clay. Vipulanandan p-q stress-strain model was used to predict the stress-stain behavior of the grouts with the curing time. The constitutive model parameters were influenced by the three variables investigated w/c, curing time and clay content.

1. INTRODUCTION

Cement grouts are used in multiple applications including construction, maintenance, tunnels, piles and wells (oil, gas and water). With the wide spectrum of applications, there is a need to understand the changes in some of the critical properties with time since the cement continues to hydrate beyond 28 days of curing which has been highlighted in some of the recent studies. There is also very limited information on the long term properties of the cement grouts.

Cement grouts, with and without additives have been widely used in the construction and maintenance of onshore and offshore infrastructure facilities for decades (Bowen 1981; Anagnostopoulos 2014; Dragonvic et al. 2014). Portland cement and oil well cements are unique in many ways because of the chemistry, bonding and setting characteristics, durability and cost (Vipulanandan et al. 2017-2018).

In the area of construction, cement grouts are used in the ducts of the post tensioned beams and the long-term performance of the beams are very much depended on the durability of the injected grouts to bond the concrete to the post-tensioned steel reinforcements and to transfer the loads. Cement grouts are used in cementing the oil, gas and water wells and the wells are expected to be productive for decades (Heinold et al. 2002; Vipulanandan et al. 2016). Also cement grouts are used for repairing these wells.

Cement grouts are used in repairing beams, pipelines and underground storage facilities in-situ and the successful operations very much depends on the durability and long-term strength of the cement grouts (Vipulanandan et al. 2014). Cement grouts are used in also stabilizing the soils to strength them for multiple applications (Vipulanandan et al. 1992; Akbulut et al. 2002). Hence there is an increasing interest in understanding and quantifying not only the variation of strength with curing time but also the long-term stress-strain behavior of the cement grouts.

For grouting applications modifiers such as various types of clays (metakaolin, bentonite) ashes, silica fume and cement kiln dust have been used. Modifiers with reactive minerals with the cement grout changes the hardening process and the flow properties of cementitious grouts (Vipulanandan et al. 2012; Celik et al. 2015; Vipulanandan and Mohammed 2015 a; Mohammed 2017). The metakaolin (clay (MK)) has been used as cement replacement material up to 30% leading to microstructure modification and high resistance to the transportation of water, the aggressive action of organic acids and diffusion of harmful ions which can lead to degradation of the matrix (Li et al. 2003; Vipulanandan et al. 2012; El-Gamal et al. 2015). To reduce the impact on the environment, clay (MK) has been used to partially replace the cementitious materials or act as an alternative cement less material.

The amount of water added to the cement grouts gives it the ability to be pumped into porous soils and fractured concrete. In general the groutability increases with the addition of water but it results in decrease in the strength and longer setting times (Akbulut et al. 2002; Vipulanandan et. al. 2012). Hence, the long-term durability of the grouts with higher water-to-cement ratio must be investigated.

2. OBJECTIVES

The focus of this study was to quantify the addition of clay (MK) and water-to-cement ratio on the setting characteristics and the compressive behavior with curing time up to 4 years for the cement grouts. The specific focuses of the study are as follows:

i. Quantify the setting times of cement grouts modified with clay (MK) and water-to-cement (w/c) ratios.
ii. Test and model the short-term (28 days) compressive stress-strain behavior and strength of cement grout modified with varying amounts of w/c ratio and clay (MK) contents.

MODELS

Vipulanandan p-q Stress-Stain Model

The behavior of strain softening materials such as polymer concrete, fiber reinforced concrete, grouted sand, contaminated clay soil and cement mortar have been predicted using the Vipulanandan p-q stress-strain relationship in the past three decades (Vipulanandan et al. 2013). Usluogullari et al. (2011) modeled the stress-strain behavior of Portland cement stabilized sand using the p-q model. Mohammed (2017) used Vipulanandan p-q model to predict the stress-strain behavior of oil well cement modified with nanoclay. In addition, the Vipulanandan p-q model was used to model the compressive stress-stain behavior of the saturated gypsum rock under different confined water pressure.

The Vipulanandan p-q stress-strain model is defined as follows:

$$\sigma = \left(\frac{\frac{\varepsilon}{\varepsilon_c}}{q + (1-p-q)\left(\frac{\varepsilon}{\varepsilon_c}\right) + p * \left(\frac{\varepsilon}{\varepsilon_c}\right)^{\frac{p+q}{p}}} \right) * \sigma_c \qquad (1)$$

where:

σ = compressive stress.
σ_c, ε_c = strength in compression and corresponding strain.
p, q= material parameters.

Material parameter q has been proved to be the ratio of secant modulus at peak stress to the initial tangent modulus. The p parameter was obtained by minimizing the error in the predicated stress - strain relationship.

3. MATERIALS AND METHODS

(a) Cement grout

ASTM C 150 -16 specified Type I Portland cement was used in preparing the grout.

(b) Clay (MK)

Commercially available metakaolin clay was used in this study. The d_{50} of 1.9 μm and the coefficient of uniformity (C_u) was 3.68. Different percentages of the metakaolin up to 10% (by the weight of dry cement) was added to the cement.

XRD characterization

To determine the chemical compositions of the metakaolin and the cement Siemens D5000 machine was used. Specimens for the XRD study were prepared from air-dried clay (MK) and cement. About 2g of samples were placed in the sample holder for the analyses. Analyses was done at 40 kV and 30 mA using the CuKα radiation. All samples were scanned for 2 sec at 0.02° increment to develop the XRD pattern.

Setting time

The Vicat needle apparatus (ASTM C 191-13) was used measure the setting times of the cement grouts modified with and without clay (MK) and w/c ratio. At least three samples were tested for each condition.

Compressive strength test (ASTM C 39-16)

The test specimen with the diameter of 50 mm and a height of 100 mm and were sulfur capped and tested at a predetermined controlled displacement rate with a displacement rate of 0.01 mm/min. The tests were done on cement grout samples after 7 days and 28 days of curing using a hydraulic compression-testing machine. Based on the information from the literature the samples were cured at 25^{o}C ± 2 and 95% humidity. Standard 10 mm resistance strain gages were used for strain measurement. At least three samples were tested for each condition.

4. RESULTS AND DISCUSSION

XRD Analyses

(i) Clay (MK)

The metakaolin clay had quartz (SiO_2) (2θ peaks at 2.0°, 25.35°, 58.40° and 63.10°), aluminum oxide (Al_2O_3) (2θ peaks at 22.25°, 33.30° and 40.75°) and magnesium oxide (MgO) (2θ peak at 22.25° and 48.75°)as shown in Fig. 1 (*a*).

(ii) Cement

The Portland cement had calcium oxide (CaO) (2θ peaks at 6.30°, 12.25°, 41.35° and 62.45°), quartz (SiO_2) (2θ peaks at 15.0°, 23.05° and 62.55°), aluminum oxide (Al_2O_3) (2θ peak at 29.50° and 32.30°), magnesium oxide (MgO) (2θ peak at 47.50° and 51.75°), calcium silicate ($2CaO.SiO_2$) (2θ peak at 47.21° and 52.01°) and tricalcium silicate (Ca_3SiO_5) (2θ peaks at 56.55°, 60.09°and 79.15°) as shown in Fig. 1 (b).

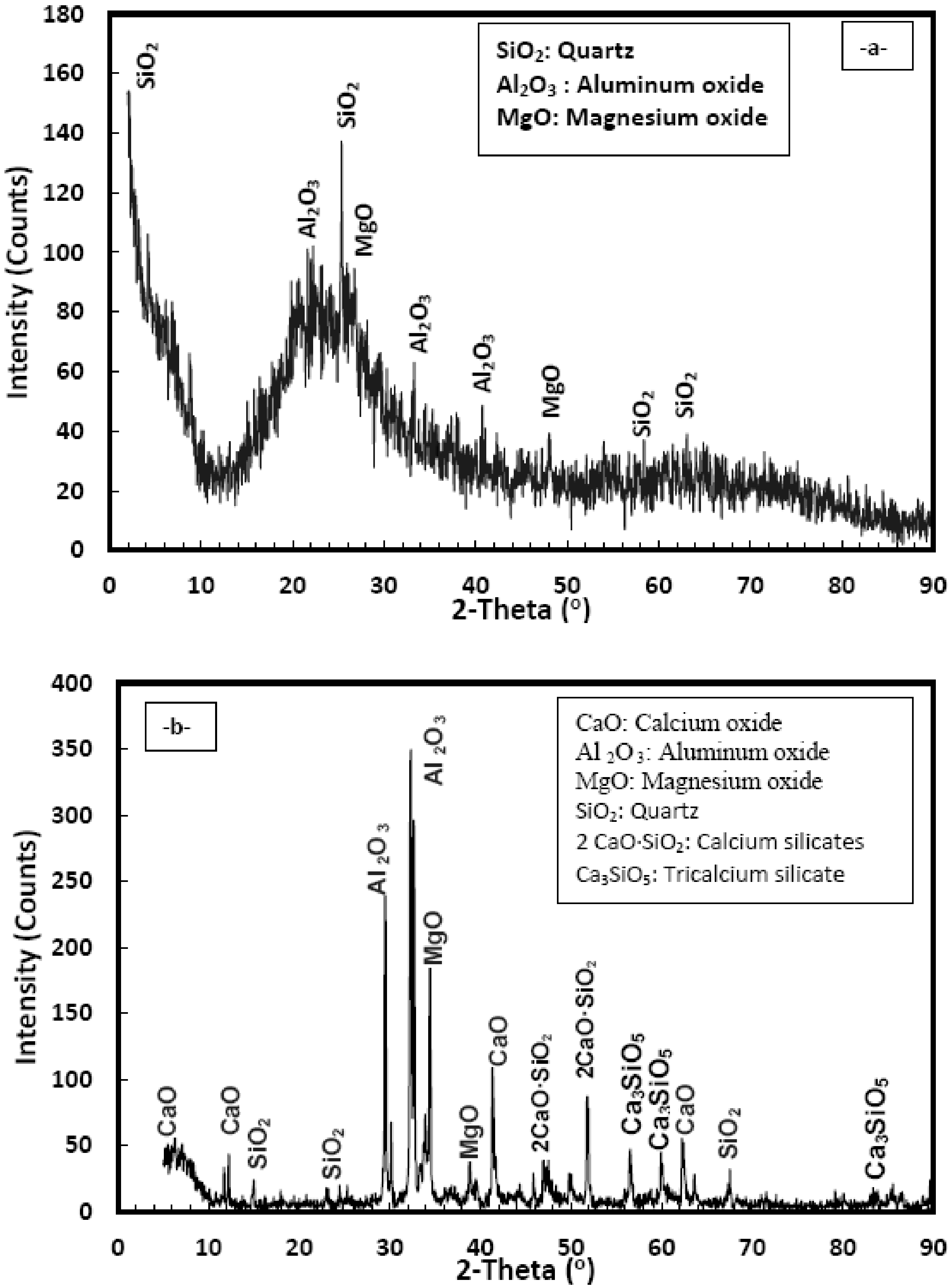

Figure 1. XRD patterns (a) Clay (MK) and (b) Cement

Setting Times

The setting times (initial and final) were measured for all the cement grout mixes. The cement grout with water-to-cement ratio of 1.0 had higher times than the cement grout mixes with w/c ratio of 0.6 as shown in Fig. 2. In addition, the setting times decreased with the addition of clay (MK).

(i) Water-to-cement ratio of 0.6

The setting times of the cement grout with w/c ratio of 0.6 with 0% of clay (MK)) was 500 min (initial) and 586 min (final) respectively as shown in Fig. 3. The addition of 10% of clay (MK) to the cement grout reduced the initial and final setting to the 280 min and 485 min, a 44% and 17% reduction respectively as shown in Fig. 2.

(ii) Water-to-cement ratio of 1.0

The setting times of the cement grout with w/c ratio of 1.0 with 0% of clay (MK)) was 646 min (initial setting time) and 978 min (final setting time) respectively as shown in Fig. 3. The addition of 10% of clay (MK) to the cement grout reduced the initial and final setting to the 580 min and 833 min, a 10% and 15% reduction respectively as shown in Fig. 2.

Compressive Behavior

Adding clay (MK) increased the compressive strength and modulus of cement grouts at the same w/c ratio. The increase in w/c ratio reduced the compressive strength and modulus of the cement grouts.

Curing Time

7 Days

Strength

0% Clay: With the w/c ratio of 0.6 the compressive strength of cement grout was 8 MPa. Increasing the w/c ratio to 1.0 reduced the strength to 2.4 MPa, 70% reduction.

10% Clay: With the w/c ratio of 0.6 the compressive strength of cement grout with 10% clay was 15.4 MPa, 92.5% increase compared to no clay. Increasing the w/c ratio to 1.0 the strength was 7.5 MPa, 51.3% reduction. With w/c ratio of 1.0, adding 10% clay increased the compressive strength by over 212.5% compared to the 0% clay cement grout.

Modulus

0% Clay: With the w/c ratio of 0.6 the initial compressive modulus of the cement grout was 4851 MPa (Table 1). Increasing the w/c ratio to 1.0 reduced the modulus to 1319 MPa, 72.8% reduction.

10% Clay: With the w/c ratio of 0.6 the initial compressive modulus of cement grout with 10% clay was 7404 MPa, 52.6% increase compared to no clay. Increasing the w/c ratio to 1.0 the modulus was 4011 MPa, 44.5% reduction. With w/c ratio of 1.0, adding 10% clay increased the compressive modulus by over 204% compared to the 0% clay cement grout.

28 Days

Strength

0% Clay: With the w/c ratio of 0.6 the compressive strength of cement grout was 14.8 MPa. Increasing the w/c ratio to 1.0 reduced the strength to 5 MPa, 66.2% reduction.

10% Clay: With the w/c ratio of 0.6 the compressive strength of cement grout with 10% clay was 24.4 MPa, about 65% increase compared to no clay. Increasing the w/c ratio to 1.0 the strength was 13.8 MPa, 43.4% reduction. With w/c ratio of 1.0, adding 10% clay increased the compressive strength by over 176% compared to the 0% clay cement grout.

Modulus

0% Clay: With the w/c ratio of 0.6 the initial compressive modulus of the cement grout was 9737 MPa. Increasing the w/c ratio to 1.0 reduced the modulus to 2955 MPa, 69.7% reduction.

10% Clay: With the w/c ratio of 0.6 the initial compressive modulus of cement grout with 10% clay was 17,968 MPa, 84.5% increase compared to no clay. Increasing the w/c ratio to 1.0 the modulus was 9293 MPa, 48.2% reduction. With w/c ratio of 1.0, adding 10% clay increased the compressive modulus by over 214% compared to the 0% clay cement grout.

Stress-strain behavior

In this study, the cement grout with two different w/c ratios modified with various amounts of metakaolin, exhibited higher modulus as shown in Fig.3. and Fig.4. The material parameters p and q in (Eqn.1) were determined based on the stress- strain behavior of cement grout with two different w/c ratios 0.6 and 1 modified with different percentage of clay (MK) (by dry weight) and the values and R^2 are summarized in Table 1. As summarized in Table 1 the parameters p and q were influenced by the w/c ratio, curing time and clay (MK) content.

(i) Curing time of 7 days

The compressive strength (σ_c) of the cement grout with w/c ratio of 0.6 and 1 without clay (MK) after curing for 7 days were 8 MPa and 2.4 MPa respectively, a 70% reduction when the w/c ratio increased from 0.6 to 1 (Table 1). The addition of 10% clay (MK) increased the strength in compression (σ_c) of the cement grout with w/c ratio of 0.6 and 1 by 93% and 213% respectively as summarized in Table 1.

The stress- strain behavior for the cement grout in compression with two different w/c ratio of 0.6 and 1modified with the different percent of clay (MK) after curing for 7 days were modeled using the Vipulanandan p-q model (Eqn. (1)). The coefficients R^2 varied between 0.98 and 0.99 (Table 1). The RMSE varied between 0.02 MPa and 0.13 MPa (Table 1).The model parameters p for cement grout with w/c ratio of 0.6 and 1 with 0% of clay (MK) after 7 days of curing varied between 0.16 and 0.21 (Table1). The model parameters q for cement grout with w/c ratios of 0.6 and 1 with 0% of clay (MK) after 7 days of curing varied between 0.91 and 0.97 based on the w/c ratio (Table 1). The Vipulanandan p-q model (Eqn. (1)) predicted the stress-strain behavior of the cement grouts very well (Fig. 3 and Fig. 4).

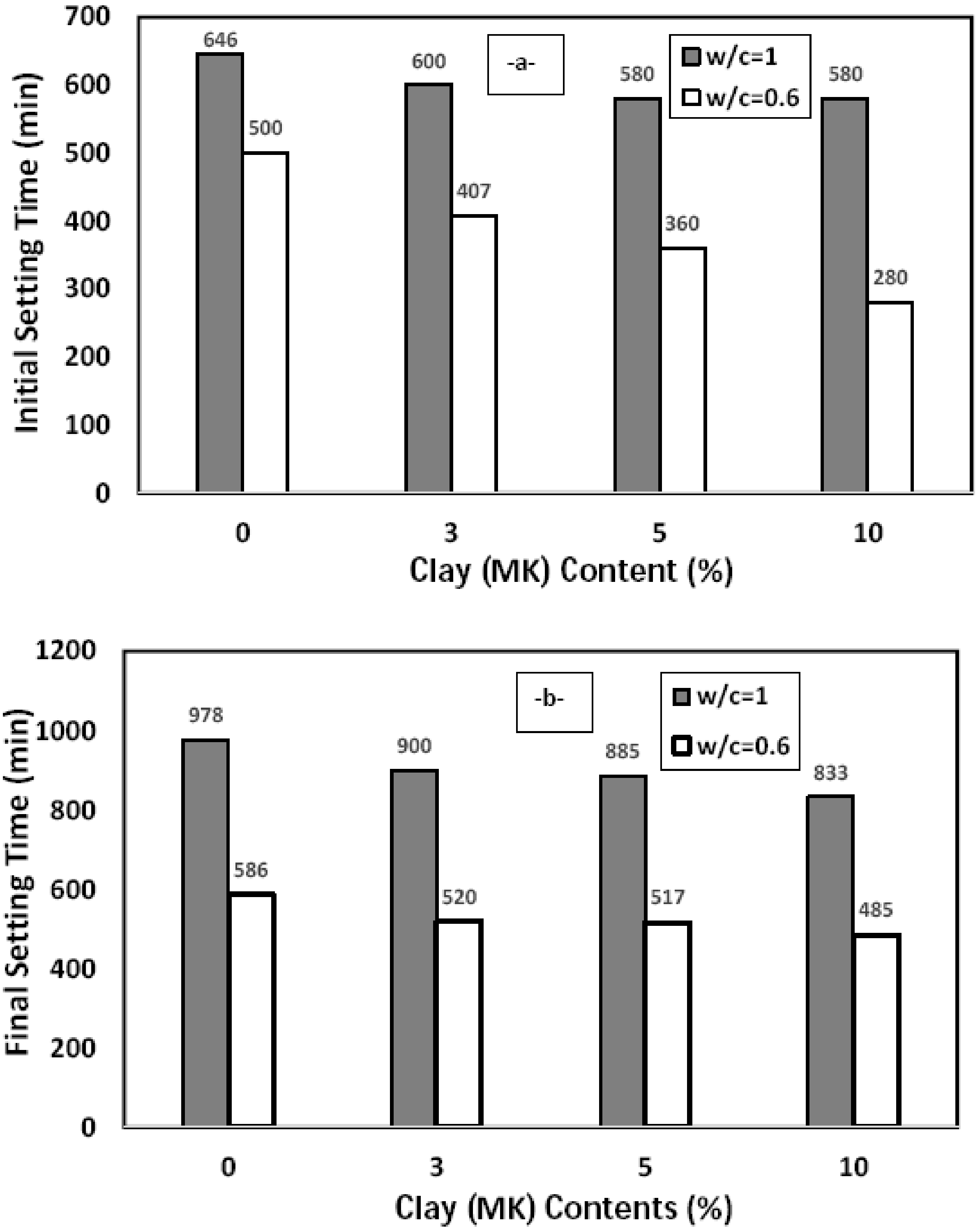

Figure 2: Setting time from Vicat needle test (a) Initial Setting Time and (b) Final Setting Time.

Table 1 Stress- strain model parameters for cement grouts modified with clay (MK)

w/c	Clay (MK) (%)	Curing time, t (days)	σ_c (MPa)	ε_c (%)	Modulus of Elasticity, E (MPa)	p	q	RMSE (MPa)	R^2
0.6	0	7	8± 1	0.17 ± 0.02	4851 ± 15	0.16 ± 0.03	0.97± 0.01	0.08	0.99
	10		15.4 ± 2	0.16 ± 0.03	7404 ± 14	0.13 ± 0.01	0.88 ± 0.01	0.13	0.99
0.6	0	28	14.8 ± 1.2	0.16 ± 0.03	9737 ± 15	0.25 ± 0.04	0.95± 0.03	0.21	0.96
	10		24.4 ±2.5	0.14 ± 0.01	17968 ± 15	0.09 ± 0.01	0.97± 0.02	0.22	0.99
1	0	7	2.4 ± 1	0.2 ± 0.03	1319 ± 10	0.21± 0.03	0.91± 0.01	0.02	0.99
	10		7.5 ± 2	0.22 ± 0.01	4011 ± 17	0.20± 0.04	0.85± 0.04	0.08	0.98
1	0	28	5.0 ± 1.5	0.18 ± 0.02	2955 ± 17	0.18± 0.02	0.94± 0.02	0.04	0.99
	10		13.8 ± 0.8	0.15 ± 0.02	9293 ± 15	0.09± 0.03	0.99± 0.01	0.13	0.99

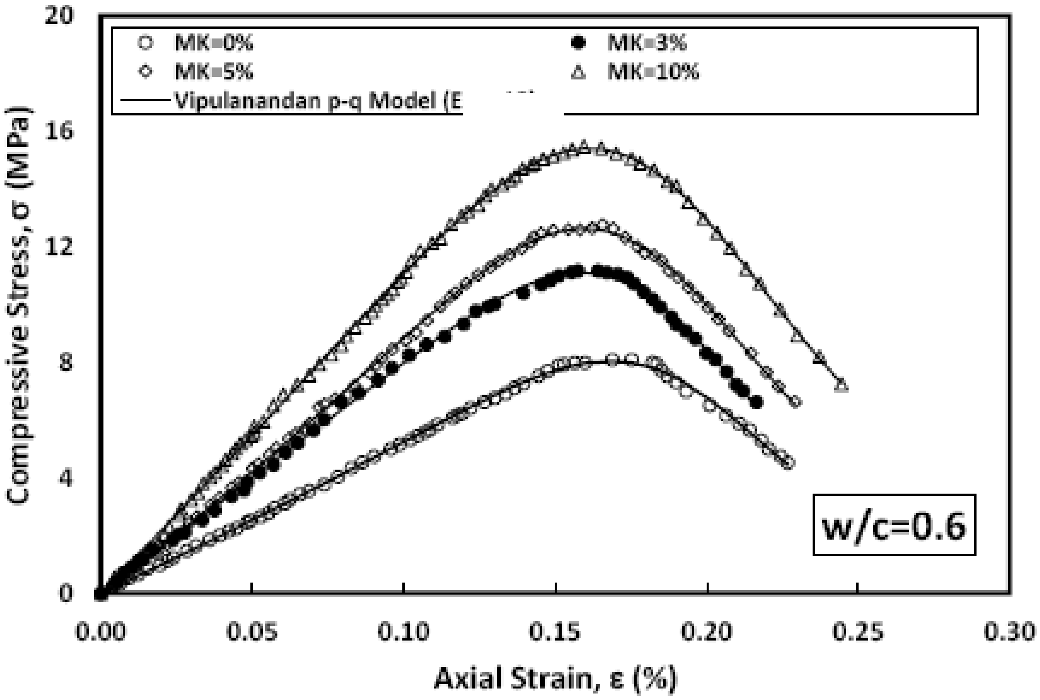

Figure 3. Measured and Predicted Compressive Stress-Strain Relationships for the Cement Grouts with Varying Clay Contents Cured for 7 days and W/C ratio of 0.6

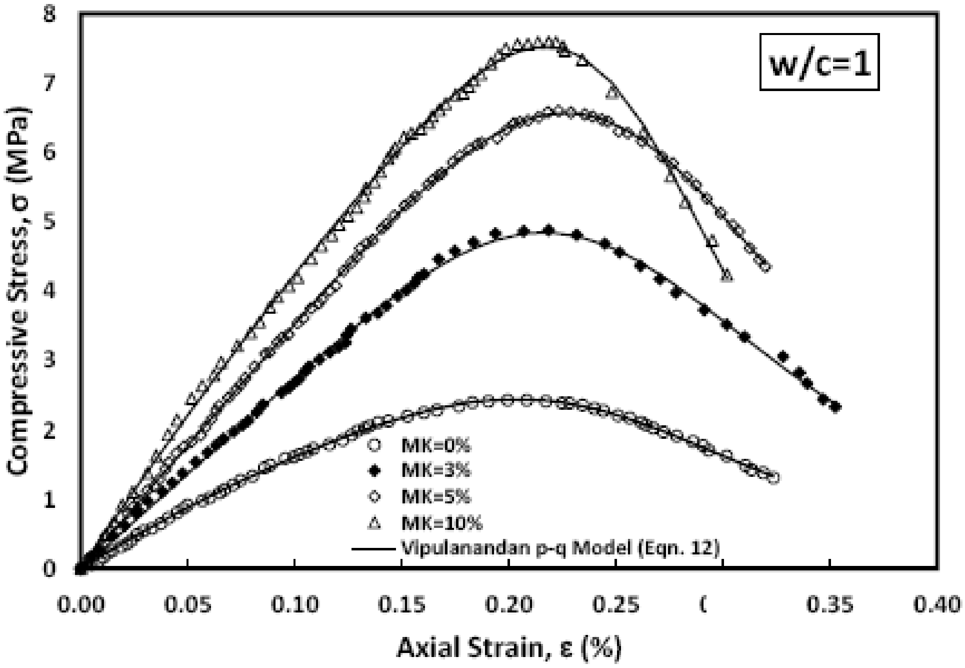

Figure 4 Measured and Predicted Compressive Stress-Strain Relationships for the Cement Grouts with Varying Clay Contents Cured for 7 days and W/Cement ratio of 1.0

(ii) Curing time of 28 days

The strength (σ_c) of the cement grout with w/c ratio of 0.6 and 1 without clay (MK) after curing for 28 days were 14.8 MPa and 5 MPa respectively, a 66% reduction when the w/c ratio increased from 0.6 to 1 respectively (Table 1). The addition of 10% clay (MK) increased the compressive strength (σ_c) of the cement grout with w/c ratio of 0.6 and 1 by 65% and 176% respectively (Table 1). The compressive stress- strain behavior of the cement grout with different w/c ratio of 0.6 and 1 after curing for 28 days were modeled using the Vipulanandan p-q model (Eqn. (1)). The R^2 varied between 0.96 to 0.99. The RMSE was varied between 0.04 MPa and 0.22 MPa (Table 1).

The parameter p for the cement grout with different percentage of clay (MK) with w/c ratio of 0.6 and 1 varied from 0.09 to 0.25 (Table 1).The parameter q for the cement grout with different percentage of clay (MK) with w/c ratio of 0.6 and 1 varied from 0.94 to 0.99 (Table 1).The R^2varied from 0.96 to 0.99 and the RMSE varied from 0.034 MPa to 0.071 MPa for 28 days of curing respectively (Table 1).

The Vipulanandan p-q model (Eqn. (1)) predicted the stress-strain behavior of the cement grouts very well (Fig. 5 and Fig. 6).

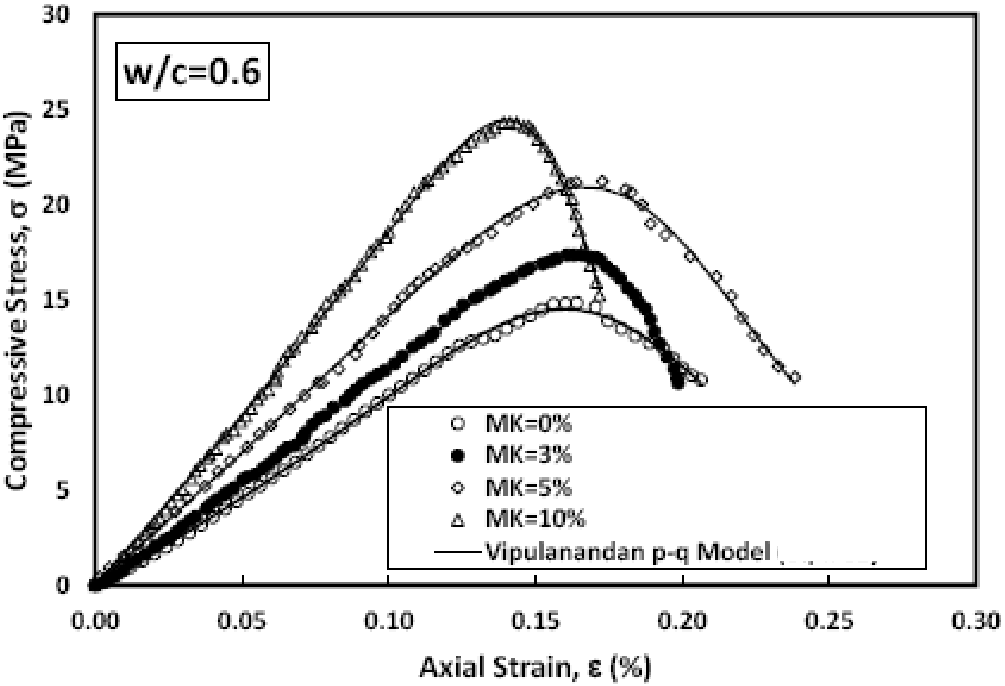

Figure 5 Measured and Predicted Compressive Stress-Strain Relationships for the Cement Grouts with Varying Clay Contents Cured for 28 days and W/C ratio of 0.6

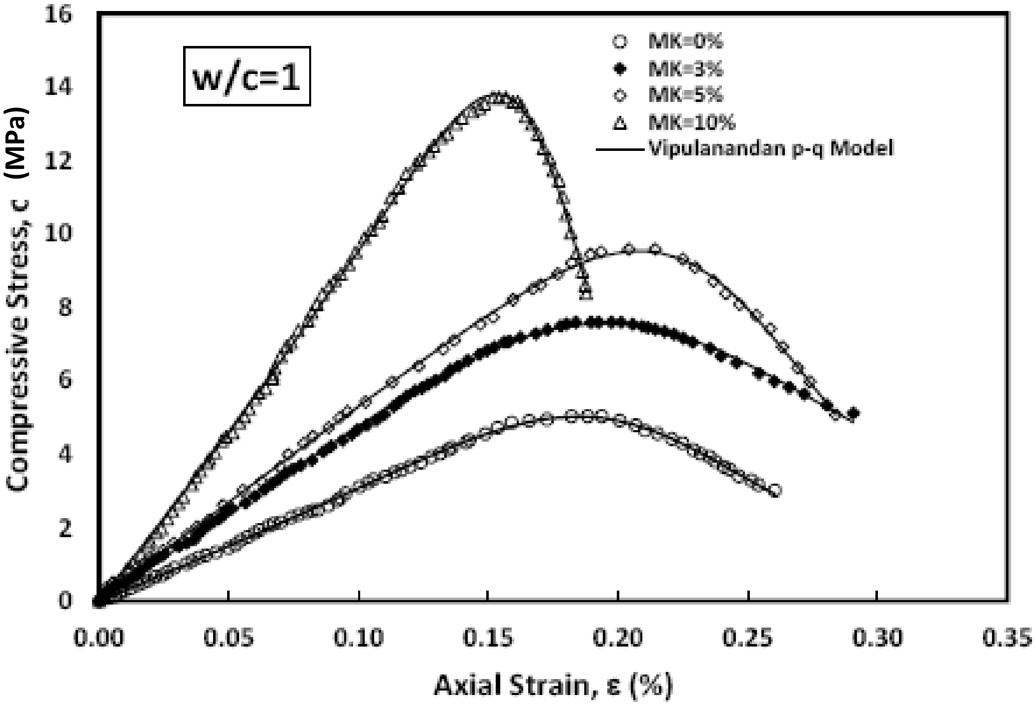

Figure 6 Measured and Predicted Compressive Stress-Strain Relationships for the Cement Grouts with Varying Clay Contents Cured for 28 days and Water-to-Cement ratio of 1.0

CONCLUSIONS

Based on the experimental and analytical modeling of the short-term compressive stress-strain behavior of cement grouts with w/c ratios of 0.6 and 1.0 and modified with up to 10% metakaolin (clay (MK) following conclusions are advanced:

1) The initial and final setting times of the cement grouts increased with the increase in water-to-cement ratio while adding the clay (MK) decreased the initial and final setting times of the cement grouts.
2) The compressive strength of cement grout decreased with increased w/c ratio but increased with the addition of clay (MK). With 10% of clay (MK), the compressive strength of the cement grouts with w/c ratio of 0.6 and 1.0 increased by 99% and 135% respectively after 1460 days (4 years) of curing compared with the 7 days of curing.
3) Vipulanandan p-q stress-strain model was used to predict the compressive stress-strain behavior of clay (MK) modified cement grouts. The model parameters were sensitive to the amount of clay (MK) content, w/c ratio and curing time..

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