Comparison Study of Dynamic Elastic Moduli of Cement Mortar and No-cement Slag Based Cementitious Mortar Activated with Calcined Dolomite with Impulse Excitation Technique

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Abstract. This paper presents the comparison of an experimental investigation on compressive strength and dynamic elastic moduli of mortars made of Ordinary Portland Cement (OPC) and ground granulated blast furnace slag (GGBFS) incorporating with calcined dolomite. Dolomite powder calcined at temperature 900°C emerged as a GGBFS activator for producing cementitious mortar binder. In this study, no-cement mortar is made by activating GGBFS with calcined dolomite by a fixed amount of 20 wt%. The compressive strengths and dynamic elastic moduli were measured at 7 and 28 days. Comparing with cement mortar, the compressive strength of no-cement mortar was found about 54.4 and 46.9% lower at ages of 7 and 28 days, respectively. Non-destructive evaluation of the dynamic elastic moduli was investigated by impulse excitation technique (IET). It measures the resonant frequencies of induced vibration signal in the flexural and torsional mode for determining the dynamic Young's modulus and the dynamic shear modulus. The Poisson's ratio was calculated by the dynamic Young's modulus and the dynamic shear modulus relationship. The results showed that the 28-day dynamic Young's and shear moduli of cement mortar were 31.91 and 14.43 GPa, respectively. The dynamic Young's and shear moduli of no-cement mortar were lower by 23.3 and 15.2% than that of cement mortar at the age of 28 days. The obtained results showed that the 28-day Poisson's ratio of no-cement mortar had a wider range between 0.177 and 0.209 than that of cement mortar which ranged from 0.180 to 0.185.

1 Introduction

Ordinary Portland cement (OPC), as a vital construction material, has reached worldwide annual production of 2.8 billion tonnes and expected to increase 4 billion tonnes per year [1]. Meanwhile, approximately 5-7% of global carbon dioxide (CO_2) emission originate from OPC production, ranging from 0.66 to 0.82 kg of CO_2 emitted for every kilogram produced [2]. On the contrary, a large amount of industrial waste by-products such as ground granulated blast furnace slag (GGBFS) is being generated every year throughout steel industries. It is reported that the annual worldwide production amount of GGBFS is 530 million ton every year [3]. With the similar chemical and mineral composition to OPC, GGBFS can be potentially used as cement replacement. The usage of GGBFS as cement replacement not only reducing the CO_2 emission but also solving industrial by-product waste disposal problem.

GGBFS without an activator does react slowly with water, so it may take longer time for a pure slag concrete made with GGBFS as the binder to reach the equivalent the 28-day compressive strength of concrete made with OPC [4]. The concrete and mortar binder made with 100% GGBFS plus activator, known as alkali-activated slag, was investigated intensively during the past few decades [5-7]. Chemical activators are commonly used as slag activators such as sodium hydroxide (NaOH), sodium silicate (Na_2SiO_3), and sodium carbonate (Na_2CO_3) [7].

Activation of GGBFS without chemical activator is feasible. Recent studies [8], [9] showed that dolomite powder ($CaMg(CO_3)_2$) being calcined at a temperature of 800-1000°C potentially used as GGBFS activator. The two-step decomposition of dolomite [10] shown as follows:

$$CaMg(CO_3)_2 \rightarrow CaCO_3 + MgO + CO_2 \quad (1)$$

$$CaCO_3 \leftrightarrow CaO + CO_2 \quad (2)$$

The formation of calcium carbonate ($CaCO_3$) and magnesium oxide (MgO) (Eq. 1) occurred at a lower temperature (Eq. 1), whereas the formation calcium oxide (CaO) (Eq. 2) takes place at a higher temperature. Several studies [11]-[13] showed that both CaO and MgO were used as potential activators for producing a GGBFS-based no-cement binder.

The impulse excitation technique (IET) is widely used techniques for determining the vibration behavior of the engineering material by measuring the resonant frequencies by non-destructive testing [14]. The IET consists in vibrating a specimen by exiting it with an impulse, capture the vibration signal with a microphone, and calculate the dynamic elastic moduli from the measured lowest flexural and torsional frequencies [15]. Some studies have shown the application of IET for determining dynamic elastic properties on building materials, for instance, the concrete at high temperatures [16], engineered stone [14], and granites [17].

The incorporation GGBFS and calcined dolomite to produce no-cement mortar still lack sufficient studies. Therefore, the objective of this study was to investigate the compressive strength and dynamic elastic moduli of no-cement mortar produced by the GGBFS activated by calcined dolomite (slag-dolomite) at the amount of 20 wt% (percentage by weight) and compare the results to cement mortar.

2 Experimental program

2.1 Materials

In the present study, type I Ordinary Portland Cement (OPC) produced by Taiwan Cement Co. Ltd., ground granulated blast furnace slag (GGBFS) obtained from CHC Resources Corporation, Taiwan, and dolomite powder, obtained from Taimax Material Co. Ltd., Taiwan, were used. Calcined dolomite was obtained by laboratory calcination, it was calcined at complete decarbonation temperature 900°C for 60 minutes [9]. The physical properties and chemical composition of OPC, GGBFS, and dolomite powder are given in Table 1. The aggregate used to produced mortar was natural river sand (<4.75 mm) with the fineness modulus (FM) of 2.99 and saturated surface dry specific gravity of 2.72.

2.2 Mix proportions and fresh mortar properties

Our previous study [9] has shown that the addition of 20 wt% calcined dolomite as GGBFS activator induced the highest compressive strength. In this study, the calcined dolomite amount was fixed by 20 wt% for producing no-cement slag-dolomite mortar. The mortar produced consist of 1 part binder and 2.75 parts of sand proportioned by mass according to ASTM C109 [18]. Mix proportions were designed by a volumetric method with a fixed water-to-binder ratio of 0.4 presented in Table 2.

The workability of mortar was attained by using the optimum dosage of superplasticizer (Type F polycarboxylic ether). Flow table test was conducted according to ASTM C1437 [19] to determine the optimum dosage of superplasticizer to obtain a mortar flow of 110±5% in 25 drops. The fresh properties with a satisfy workability of slag-dolomite mortar is shown in Figure 1.

Table 1. Physical properties and chemical composition of OPC, GGBFS, and raw dolomite.

Parameters	OPC	GGBFS	Dolomite
SiO_2, %	20.42	33.54	2.71
Al_2O_3, %	4.95	13.00	-
CaO, %	61.96	39.85	90.36
K_2O, %	-	-	0.23
MgO, %	3.29	6.90	1.84
SO_3, %	2.40	1.67	-
Fe_2O_3, %	3.09	0.50	0.52
L.O.I, %	1.75	4.54	4.34
Specific Gravity	3.15	2.83	2.70

Table 2. Mortar mixtures (units: kg/m^3).

Code†	Water	OPC	GGBFS	CD	Sand	SP
M-OPC	230	575	-	-	1552	2.86
M-SD	226	-	453	113	1558	0.52

Notes: M-OPC = ordinary Portland cement mortar, M-SD = slag-dolomite mortar, CD = calcined dolomite, SP = superplasticizer (type F)

2.3 Mortar specimens preparation

The 50-mm cubic and 100×50×25 mm platy mortar specimens were made in triplicate to be tested for determining compressive strength and dynamic elastic moduli. Mortar specimens were cast by pouring fresh mortar mixture into the cubic molds, which then was tamped by hand to ensure the complete consolidation of the mortar, and towel finished. All samples were demolded after 24 hours and cured in saturated lime water according to ASTM C511 [20] at a temperature of 25±2°C.

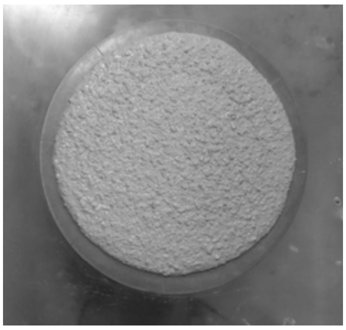


Fig. 1. Workability of the slag-dolomite mortar.

2.4 Testing method

The compressive strength test of 50-mm cubic slag-dolomite mortar specimens was determined by uniaxial compression according to ASTM C109 [18] using a computer-controlled hydraulic compression testing machine with a 2000-kN capacity.

The RFDA Basic instrument (Resonant Frequency and Damping Analyzer, developed by Integrated Material Control Engineering, Belgium) was used to analyze the dynamic elastic moduli of slag-dolomite mortar specimens by the impulse excitation method (IET) according to ASTM E1876 [21]. The IET measures the resonant frequencies in order to calculate the dynamic elastic moduli on the non-destructive basis.

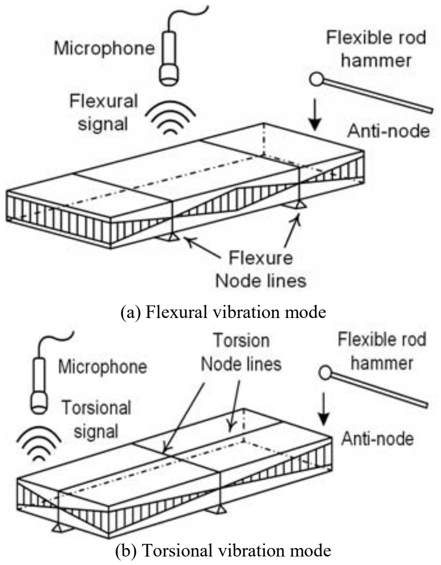


Fig. 2. Schematic representation of both flexural and torsional vibration modes applied in platy specimen [16].

Li et al. [22] confirmed that the dynamic elastic moduli of OPC mortar platy specimens with aspect ratio 2:1 give an error about 0.11-1.64% comparing with the impact resonance method. In this study, the 100×50×25 mm platy specimen with aspect ratio 2:1 was positioned on the testing support to create flexure (Figure 2a) and torsion (Figure 2b) node lines. The specimens were gently tapped on the anti-node by a flexible rod hammer by 0.7-mm sphere ball in order to induce both flexural and torsional vibration modes. The vibration signal was then captured by a 16 kHz microphone and sent to RDFA software. The software extracted the data by using Fast Fourier Transformation (FFT) in order to determine both flexural (f_f) and torsional (f_t) frequencies. The dynamic Young's modulus (E_{dyn}) and shear modulus (G_{dyn}) was calculated by using Eq. 3 and Eq. 4 respectively.

$$E_{dyn} = 0.9465\left(\frac{m \cdot f_f}{w}\right)\left(\frac{l^3}{t^3}\right)T \tag{3}$$

$$G_{dyn} = \left(\frac{4 \cdot l \cdot m \cdot f_t^2}{w \cdot t}\right)\left(\frac{B}{(1+A)}\right) \tag{4}$$

$$\nu_{dyn} = \frac{E_{dyn}}{2G_{dyn}} - 1 \tag{5}$$

where m, l, w, and t represents specimen mass (g), length, width, and thickness (mm), f_f and f_t are the flexural and torsional frequency (Hz), and T, A, and B are correction coefficients which can be found in ASTM E1876 [21]. Dynamic Poisson's ratio (ν_{dyn}) was determined from the relationship between dynamic Young's modulus and shear modulus as shown in Eq. 5.

3 Results and discussion

3.1 Comparison of compressive strength

The compressive strength tests of hardened cement mortar (M-OPC) and slag-dolomite mortar (M-SD) were carried out at ages of 7 and 28 days. The compressive strength comparisons are graphically represented in Figure 3. The compressive strength of slag-dolomite mortar at ages of 7 and 28 days reached about 24.4 and 30.6 MPa, which was lower about 54.4 and 46.9% lower than cement mortar. The compressive strength of slag-dolomite mortar proved to be increased with curing time due to GGBFS hydration process. The positive effect from GGBFS activated by calcined dolomite showed that after 7 days of hydration the compressive strength of slag-dolomite mortar was approximately 79.6% of that at the age of 28 days. The enormous difference of compressive strength between cement mortar and slag-dolomite mortar related to the distinctive hydration products.

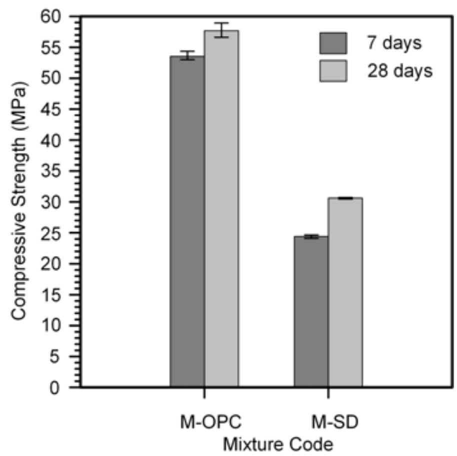
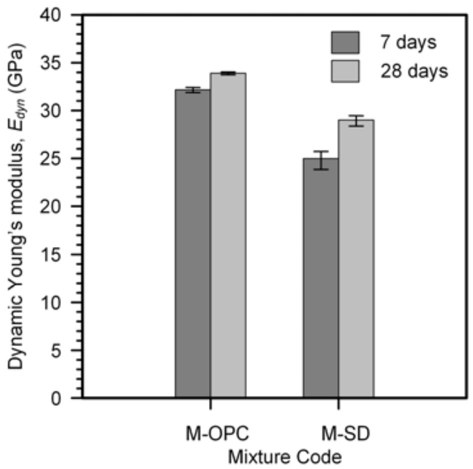


Fig. 3. The compressive strength comparison of hardened cement mortar (M-OPC) and slag-dolomite mortar (M-SD) at ages of 7 and 28 days.

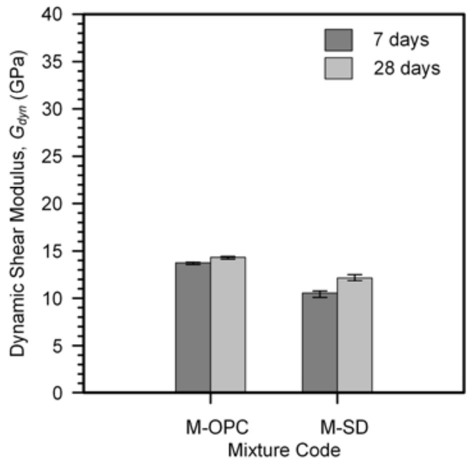
3.1. Comparison of dynamic elastic moduli

The time domain vibration signals acquired from either flexural or torsional mode (Figure 2) were converted to the frequency domain by FFT using RFDA software. Then, the flexural and torsional frequencies were used to calculate dynamic Young's (E_{dyn}) and shear modulus (G_{dyn}). The dynamic Poisson's ratio (ν_{dyn}) was directly calculated from the dynamic Young's modulus and the dynamic shear modulus relationship as shown in Eq. (5). The comparison of dynamic elastic moduli and Poisson's ratio of cement mortar and slag-dolomite mortar are shown in Figure 4. The dynamic Young's modulus was 32.2 and 33.9 GPa, while the shear modulus was 13.8

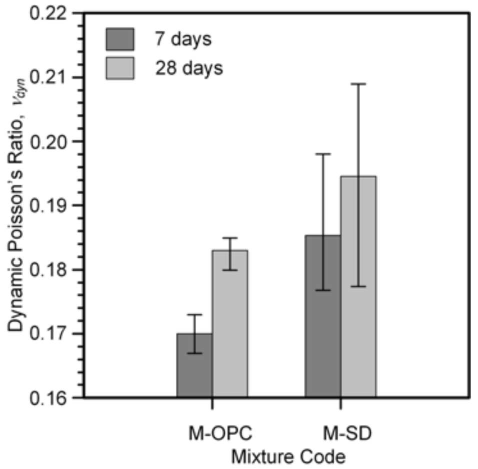
and 14.3 GPa, for cement mortar at ages of 7 and 28 days, respectively. For slag-dolomite mortar, the dynamic Young's modulus was lower by 25.8 and 14.4% while the shear modulus was lower by 23.3 and 15.2% at ages of 7 and 28 days, respectively. As a porous material, the 28-day Poisson's ratio of cement mortar was found in the range of 0.180 to 0.185, whereas the 28-day Poisson's ratio of slag-dolomite mortar had a wider range between 0.176 and 0.209.



(a) Dynamic Young's modulus



(b) Dynamic shear modulus



(c) Dynamic Poisson's ratio

Fig. 4. The dynamic elastic moduli and Poisson's ratio comparison of hardened cement mortar (M-OPC) and slag-dolomite mortar (M-SD) at ages of 7 and 28 days.

4 Conclusion

The present study evaluated the comparison of compressive strength and dynamic elastic moduli of hardened cement mortar and no-cement slag-dolomite mortar. The following conclusions were drawn:

(1) The compressive strength of cement mortar was 53.5 and 57.7 MPa at ages of 7 and 28 days, respectively, while slag-dolomite mortar reached 24.4 and 30.6 MPa at ages of 7 and 28 days.

(2) Associated with the compressive strength results, it can be observed that no-cement mortar made with GGBFS incorporating with calcined dolomite had lower dynamic elastic moduli than cement mortar. The dynamic Young's modulus of slag-dolomite mortar was lower by 25.8 and 14.4% while the shear modulus was lower by 23.3 and 15.2% at ages of 7 and 28 days.

(3) Mortar composed of a binder and fine aggregate that lead to a porous material. The Poisson's ratio of porous material varied based on its porosity. From results obtained, it can be observed that the slag-dolomite mortar had a wider range of Poisson's ratio (0.177-0.209, at age of 28 days) than that of cement mortar (0.180-0.185, at age of 28 days). Therefore, it can be concluded that the cement mortar had less porosity than slag-dolomite mortar.

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