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Effect of elevated temperatures on properties and color intensities of fly ash mortar

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Abstract. This research examines the engineering properties and color intensities of mortar containing different amounts of fly ash (0, 5, 10 and 20%) mixed at different water-to-binder ratios (w/b = 0.23, 0.47 and 0.59) and exposed at different temperatures (T = 25, 100, 200, 400, 600 and 800^oC). Results show that there is greater mass loss on ignition with high w/b and higher temperatures. In addition, the color channel image analyzer (Windows software written in Delphi) is utilized to study the relationship between the curing temperature and intensity of three primary colors, red, green and blue (RGB), of the fly ash mortar specimens. The results show that the RGB intensities on the specimen surface increases from that at 25^oC. The mortar specimen becomes white with increase in w/b but without the addition of fly ash. Moreover, for mortar specimens with greater content of fly ash, red on the specimen surface has the greatest increase in intensity at elevated temperature. Observation the variations in color on the specimen surface may help estimate the highest elevated temperatures that concrete structures can withstand.

Keywords: elevated temperature; fly ash; mortar; image analyzer.

1. Introduction

Taiwan is a small island under marine environment, and concrete structures along its coast are prone to corrosion due to the sulfate attack by brine and sea breeze. Using concrete with appropriate fly ash content can enhance its resistance to sulfate attack, and improve its workability and durability (Helumth 1987).

Under the terrorist attack on September 11, two World Trade Center towers collapsed within a short time in front of millions of viewers due to the loss in strength and stiffness at elevated temperature. The heavy casualties involved have called to attention the performance of construction materials when exposed to extreme temperatures (Ravindrarajah, *et al*. 2002)

In recent years, the research and development by domestic and foreign experts have made available high-performance concrete (HPC) with high strength and high workability. In mixing HPC, gravel sand or Portland cement is substituted by the addition of fly ash in order to improve workability, enhance durability, minimize environmental pollution and CO_2 emission, reduce production cost and utilize resources efficiently (Bouzouba and Fournier 2003). Nonetheless, research on the effect of high temperature on properties of concrete with fly ash added has been scarce but merits further study. A proper amount of fly ash would give a better and stronger concrete mixture under

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high temperature and pressure (Paya, *et al*. 2003). Concrete containing fly ash is of a denser structure and has better fire resistance compared with that without fly ash added. This study examines the impact of fly ash addition on properties of mortar mixed at different water-to-binder ratios (w/b) and at high temperature. It is hoped that knowing the high-temperature properties of fly ash concrete can contribute to a better understanding of the resource recovery of fly ash and its degradation under high temperature (Wang and Hwang 1997).

Table 1 Physical properties and chemical compositions of cement and fly ash

Items	OPC	Class F Fly ash
Physical properties		
Specific gravity (g/cm^3)	3.15	2.19
Fineness		
Passing 45 μm (%)	94.0	75.2
Specific surface, Blaine (cm^2/g)	3150	2970
Mortar cubes strength (MPa)		
7-day	26.6	-
28-day	32.1	-
Pozzolanic activity index (%)		
7-day	-	79.6
28-day	-	89.2
Time of setting, Vicat test (min)		-
Initial setting time (h: min)	85.0	-
Final setting time (h: min)	151.0	-
Air content of mortar (%)	5.5	-
Chemical composition (%)		
SiO_2 (S)	22.0	54.2
Al_2O_3 (A)	5.6	31.4
Fe_2O_3 (F)	3.4	2.3
CaO (C)	62.8	2.8
MgO (M)	2.6	0.6
Na_2O (Na)	0.4	0.2
K_2O (K)	0.8	1.2
Na_2O + 0.658 K_2O	0.9	1.0
P_2O_5 (P)	0.2	0.3
TiO_2 (T)	0.5	1.4
SO_3 ($\check{S}$)	2.1	0.1
Loss on ignition (LOI)	0.5	3.8
Bogue potential compound composition		
C_3S	40.1	-
C_2S	32.8	-
C_3A	8.9	-
C_4AF	10.5	-
Dissolve Residual	0.2	-

Under elevated temperature, a chemical change occurs in the concrete whose surface color changes with the temperature (Lin, *et al.* 2004, Luo, *et al.* 2003), although the differences can hardly be determined by the naked eye. This study aims at to observe the variations in surface color of the mortar specimen at elevated temperature using image analysis technology and by eye, and verifies the heat-resistant property of fly ash concrete.

2. Experimental study

2.1. Materials

Table 1 lists the chemical components and physical properties of cement and fly ash used in this study. The specific gravity of fine aggregate, absorption capacity and fineness modulus are 2.65, 1.4% and 2.91, respectively.

2.2. Specimen preparation

Table 2 lists the experimental variables employed for mixing fly ash mortar at different w/b according to ASTM C109. The fly ash mortar thus obtained is made into 5-cm cubic specimens, which are moisture cured for 28 days prior to testing.

2.3. Elevated-temperature test

Specimens for elevated-temperature test are first placed in a high-temperature furnace at 200°C and 400°C for two hours and then at 600°C and 800°C for four hours, followed by rapid cooling to ambient temperature. Photos of specimens after heating are taken for color observation. The mass after loss on ignition (LOI) is then measured. Under high temperature, the hydrated cement product will be decomposed. Crystal water from C-S-H gel and calcium hydroxide will lose and $CaCO_3$

Table 2 Experimental variables

Items	Variables
Material	Sand, water and Type I Portland cement
Mix ratio of cement to sand	1:2.75
w/b ratio	0.23, 0.47 and 0.59
Specimen size	50 mm × 50 mm × 50 mm
Moisture curing condition	Temperature: 25°C Humidity: 100%; for 28 days
Heating temperatures	200°C, 400°C, 600°C and 800°C for 30 minutes
Rate of temperature rise	5°C/min for 0-600°C 2°C/min for 600-800°C 1°C/min for 800-1000°C
Image acquisition	Photographed in a dark room Temperature: 27°C; Humidity: 77%
Fly ash content	0%, 5%, 10% and 20%
Age	3, 7, 14 and 28 days

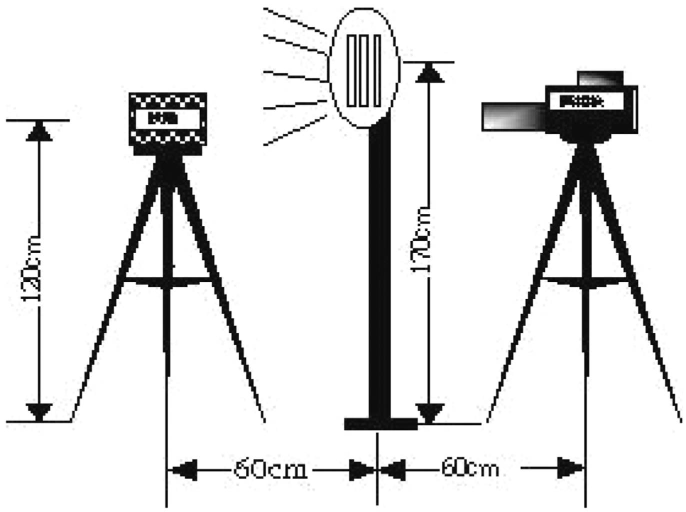

Fig. 1 Schematically drawing of photo taken for color intensity measuring

decompose into CO_2 and CaO, resulting in a decrease in mass after ignition. Measuring the changes in LOI mass under different temperatures can help explain the behavior of compressive strength and fire resistance ability of the fly ash mortar.

2.4. Image analysis

Specimens mixed with different w/b for image analysis are placed in a high-temperature furnace with temperature rising from 0°C to 600°C at 5°C/min and from 600°C to 800°C at 2°C/min. Changes in color at different temperatures are observed. In addition, fly ash mortar specimens are held for 30 minutes at ambient temperature, 200°C, 400°C, 600°C and 800°C and then removed from the furnace for further examination of their properties.

Experimental setup for image acquisition includes a digital camera supported on tripod at a distance of 120 cm from the specimens, as is shown in Fig. 1. Stationary images of the specimens are obtained and transmitted to the computer for further analysis using the image color intensity analyzer. The image color intensity analyzer was developed by Lin *et al*. (2004) and runs on a Windows program. The software was written under the Delphi platform, which is a Pascal-based object-oriented software development package. Functions such as “color intensity histogram” and “average, standard deviation and reliable ranges of intensity”, among others are implemented in the software.

3. Results and discussion

3.1. Specimen appearance

Fig. 2 shows the changes in appearance of mortar specimens mixed at w/b = 0.47 under different temperatures and with different fly ash contents. It can be seen the fly ash mortar specimens began

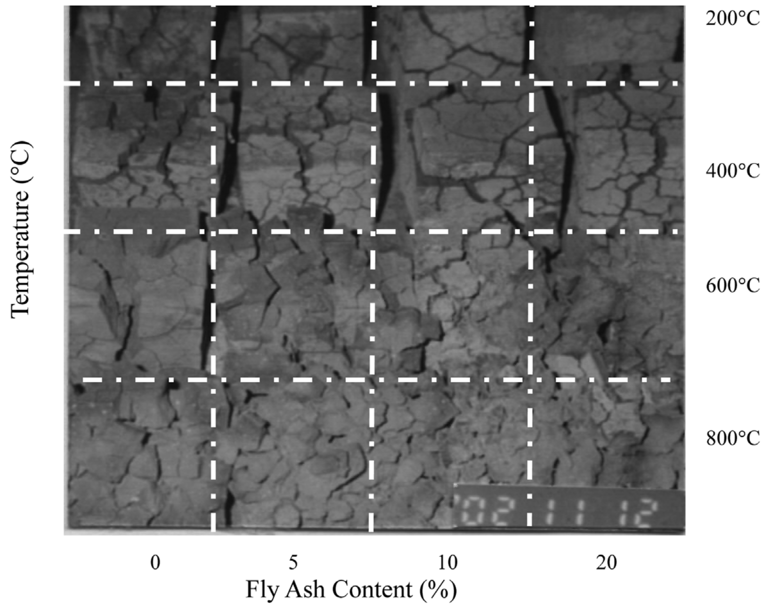

Fig. 2 Photos of fly ash mortar specimens under different temperature (w/b = 0.47)

to fracture even from temperature of 200°C. Similar to common mortar, mortar specimens with lower fly ash content show greater increase in volume after heating. And, the higher the temperature the more likely the specimens will crack. At elevated temperature, mortar specimens with higher fly ash content (20%) seems slightly expanded although the unvoiced crack as compared to others. The one at temperature of 200°C seems intact. This is in agreement with the findings of Ramlochan, *et al.* (2003). Such phenomenon can be attributed to the hollow spherical feature of fly ash particle and the increase in free water and initial porosity of mortar after the addition of fly ash. The power of expansion of water vapor due to heating hence will be reduced for those with high amount of fly ash addition.

3.2. Absorption capacity

The absorption capacity of mortar specimen is determined by the method similar to ASTM C127 for aggregate. Fig. 3 displays the relationship between absorption capacity and amount of fly ash contained in the mortar specimens with different w/b ratio. As can be seen, absorption capacity is higher at higher w/b ratio, greater the fly ash content and shorter the curing duration. However, there is no significant difference in absorption capacity of mortar specimens with different fly ash contents at w/b = 0.23. This lower absorption capacity can be attributed to the small number of pores present in these specimens. At the same curing age and w/b, fly ash content below 20% has little effect on the absorption capacity.

3.3. LOI mass

Fig. 4 shows the LOI % under elevated temperature for mortar specimens with 20% of fly ash content and different w/b. It indicates the higher the w/b ratio and the temperature, the greater the

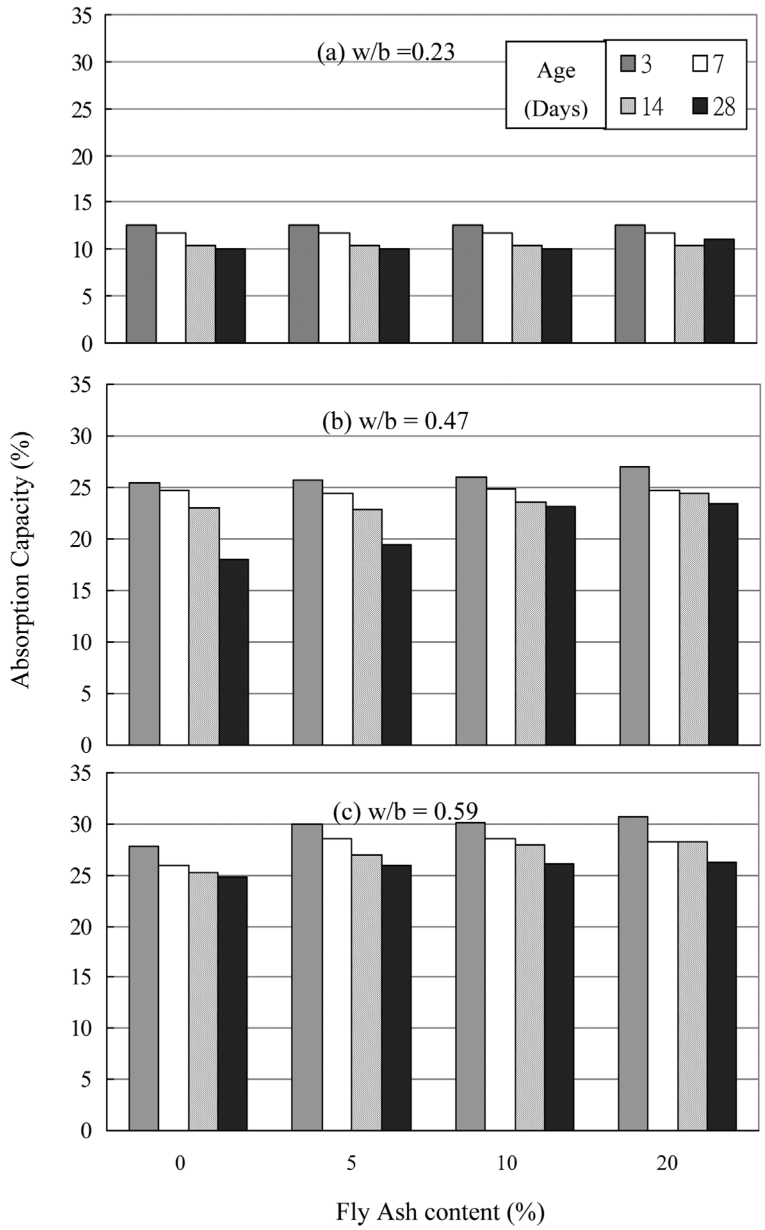

Fig. 3 Absorption capacity of fly ash mortar specimens

LOI. High w/b implies more water content; in other words, higher moisture content per unit volume. Concrete with high water content is more likely to crack and expand whatever the quality is; and hence the higher the water content the greater the danger of fracture will happen. This shows that greater w/b will enhance internal porosity and increase water absorption thus resulting in greater LOI %.

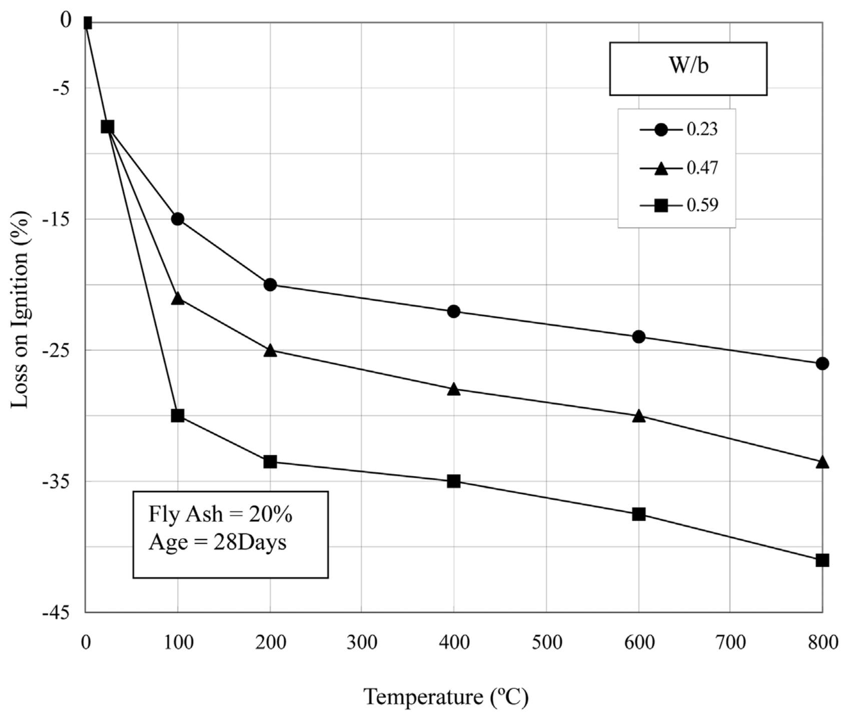

Fig. 4 Loss on ignition of mortar specimens with 20% fly ash content and different w/b ratio under elevated temperature

Table 3 Compressive strength of fly ash mortar cured for 28 days and then heated at 600°C Unit: kgf/cm^2

W/b	Fly Ash Content (%)			
	0	5	10	20
0.23	350	280	280	185
0.47	100	85	180	150
0.59	-	30	50	80

3.4. Compressive strength of fly ash mortar after heating

Table 3 indicates the peak strength of fly ash mortar moisture cured for 28 days and then heated at 600°C. It clearly shows that the higher the w/b ratio and the amount of fly ash addition the lower the compressive strength of mortar. The addition of fly ash tends to reduce the disruption of mortar specimen heated at 600°C especially with w/b = 0.59.

3.5. Relationship between RGB intensity and temperature

Fig. 5 depicts the relationship between RBG intensity and temperature for fly ash mortar mixed with w/b = 0.47 and fly ash contents of 0%, 5% and 10%. The primary color of each mortar specimen is the vertical intensity of RGB at 25 °C, and seems dark grey. The addition of fly ash

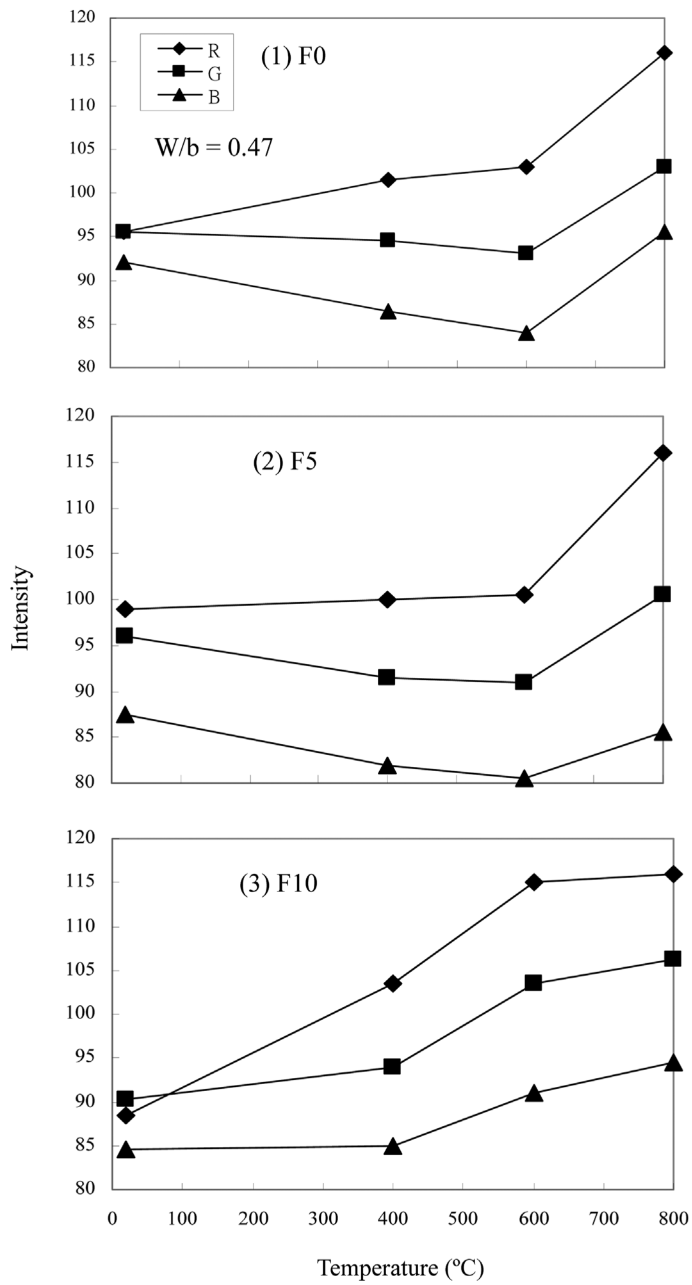

Fig. 5 Relationship between RBG intensity and temperature of fly ash mortar with w/b = 0.47

tends to be darker than that without fly ash before heating. The result in Fig. 5 shows with temperature increases from 25°C to 600°C the intensity of both G and B decrease while that of R increases with fly ash content less than 5%. This may indicate the significant change in the chemical bonding and fly ash color turn to like brick. As temperature between 600°C and 800°C, the intensity of all three colors increase obviously, and the sequence is R, G and B. By visual

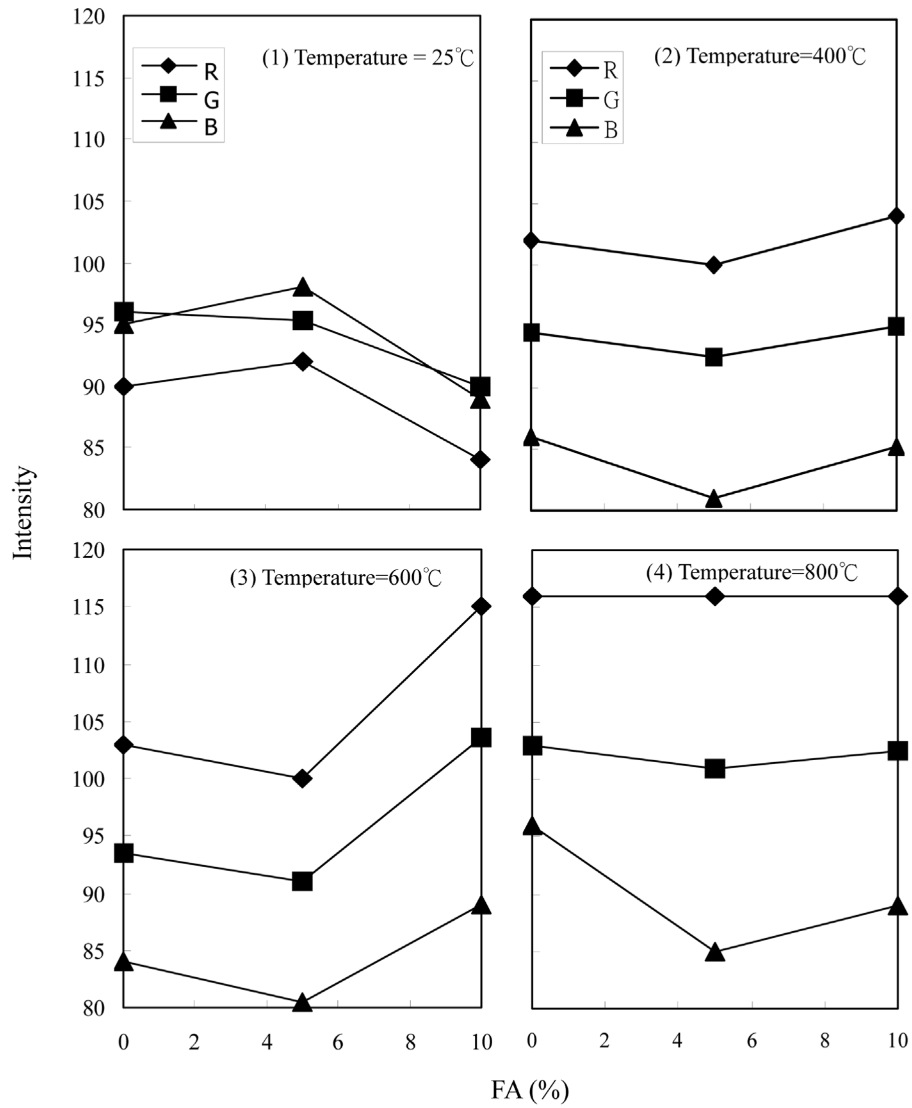

Fig. 6 Relationship between RBG intensity and fly ash mortar at different temperature (w/b = 0.47)

inspection of fly ash mortar, as fly ash content greater than 10% the surface color change from dark gray to light gray as the temperature rising. It implies the conversion of chemical bond of hydration product and destruction of mortar specimen.

3.6. Relationship between RGB intensity and fly ash content

Fig. 6 shows the relationship between RBG intensity and fly ash content for mortar with w/b = 0.47 at temperatures of 25^{o}C, 400^{o}C, 600^{o}C, and 800^{o}C. As can be seen, intensity of the three primary colors changes with fly ash content. At high temperature and increase in fly ash content to 10%, the intensity of R becomes much enhanced. Color intensity of the specimen surface changes as a result of chemical reaction and becomes bright gray, indicating that addition of fly ash may increase the heat resistance of the mortar as comparing the photo in Fig. 2.

3.7. Relationship between RGB intensity and w/b

Fig. 7 displays the relationship between RBG intensity and w/b for fly ash mortar at temperatures of 25°C and 400°C. As can be seen, at w/b ratio = 0.23, the intensity of the three primary colors at

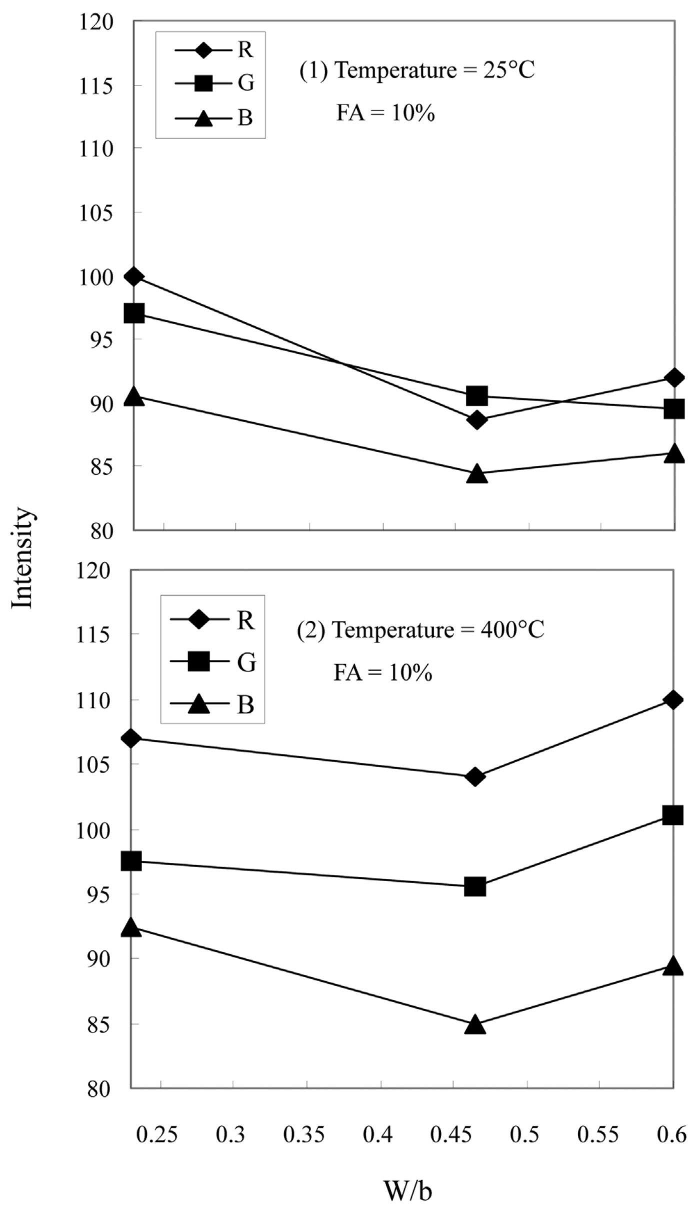

Fig. 7 Relationship between RBG intensity and w/b of fly ash mortar at temperatures of 25°C and 400°C

25°C are higher than other w/b ratio. With increase in temperature to 400°C and w/b = 0.59, the color intensities all rise significantly, causing the specimen surface to turn from dark gray to bright gray. This indicates that mortar with fly ash content of 10% and higher w/b ratio has better heat resistance as comparing the compressive strength in Table 3 and destruction pattern in Fig. 2.

4. Conclusions

(1) Under elevated temperature, fly ash mortar specimens, except the one with 20% fly ash addition and at 200°C, will fracture and crack easily, regardless of the w/b employed. On the other hand, mortar specimens with higher fly ash content, say 20%, may hold its shape and surface intact under high temperatures.

(2) Mortar specimens with higher w/b and greater fly ash content (20%) show higher absorption capacity and LOI. %.

(3) At 600°C and lower w/b ratio (0.23), mortar specimens with less fly ash content have high strength. At higher w/b the greater the fly ash content (20%) the better the strength..

(4) Under elevated temperature, the intensity of R significantly increases on the specimen surface, followed by G and B. With the increment in fly ash content, the specimen surface color changes to bright gray at higher temperatures. This indicates that concrete containing fly ash will turns red as exposure to fire or at high temperature.

(5) At 400°C and high fly ash content, chemical reaction such dehydration occurs on the specimen surface, turning it from dark gray to bright gray by visual observation.

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