

# Compressive Strength Development of Inorganic Polymeric Mortars: Effects of Water Glass and Curing

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**Abstract.** We studied the development of compressive strength of inorganic polymeric mortars with and without water glass and different curing conditions. Ten different mixtures of inorganic polymer mortar were separated into two groups. Various mixtures of fly ash, sodium hydroxide solution, water glass and clean river sand were made and cured in two ways: in oven at 60 °C for 48 hours and under ambient conditions. Compressive strengths were measured over 90 days. Results showed that water glass increases the compressive strength of these mortars but curing with high temperature reduced it. Moreover, mixtures with water glass cured at 60 °C had the highest compressive strength (62.0 MPa) at 90 days. However, mixtures without water glass and cured under ambient condition had sufficient compressive strength for normal concrete work.

## Keywords:

Inorganic polymer mortar, curing temperature, compressive strength

## 1. Introduction

The cement industry has been identified as one of biggest sources of carbon dioxide released to the atmosphere. Davidovits [1, 2] reported that producing one ton of cement releases one ton of carbon dioxide. USGS reported that world cement consumption increased from 2.52 billion tons in 2006 to 3.36 billion tons in 2010 [3]. With this increasing rate, the global warming becomes a problem faster than expected. Reducing cement use might alleviate this situation. Geopolymer, an inorganic polymer, is an alternative material that has a potential to replace cement concrete. It can be produced with a wide range of compressive strengths and thus can replace normal or high strength concrete, even light weight porous concrete [4-6]. However, two key problems with geopolymers are their high viscosities and curing conditions. Geopolymer has a very high viscosity due to its mix proportion [7-9]. Viscosity depends on the amount of silica compound in the mixture [7]. Curing at 60 – 80 °C for 24 – 48 hours enhances the compressive strength [10-13]. This discourages using geopolymer in place of conventional concrete in real work. Moreover, here we have studied a wider range of mixtures than specified by Davidovits'

patent [14], because very different compositions from geopolymer could meet the requirements of real work.

Curing conditions described to date are not practicable at a construction site. Therefore, this study focused on the effects of curing temperature on compressive strength of inorganic polymer mortars. Two curing conditions; 60 °C in an oven and ambient conditions were assessed and compressive strengths of traditional geopolymer mortar and its variants, inorganic polymer mortars, were measured after 7 to 90 days.

## 2. Experimental Program

### 2.1 Materials

Fly ash (FA) collected from the Mae Moh lignite power plant (Lampang, Thailand; 18°17'45"N 99°45'00"E) was used as inorganic polymeric base, because of its known properties [15]. Fly ash mostly contains silica and alumina that are necessary for polycondensation of alumino-silicate. Moreover, its shape increases workability of the fresh mixture of inorganic polymer. The chemical composition is in Table 1.

Chemical compound	FA	WG
SiO <sub>2</sub>	37.4	33.3
Al <sub>2</sub> O <sub>3</sub>	19.6	-
CaO	16.2	-
Fe <sub>2</sub> O <sub>3</sub>	14.6	-
SO <sub>3</sub>	5.1	-
MgO	4.0	-
K <sub>2</sub> O	2.2	-
TiO <sub>2</sub>	0.5	-
Na <sub>2</sub> O	-	15.4
Other oxides	0.4	-

**Table 1** Chemical composition of fly ash (FA) and water glass (WG) (wt %)

Sodium silicate solution or water glass (WG) and sodium hydroxide solution (NaOH) were used as the liquid portion of the mixtures. The sodium hydroxide concentration was varied from 10 to 18 M. Sodium hydroxide flakes with 98% purity were used. It was diluted with tap water to obtain the required concentrations. The solution was allowed to cool to about 30°C before use. The ratio of the sodium silicate solution to sodium hydroxide solution was varied from 2.0 to 0.0, i.e. some mixtures contain no water glass to reduce its viscosity. Because, Provis and van Deventer reported that increasing SiO<sub>2</sub> content increased the viscosity of geopolymer mixtures [7].

both FA and WG contain SiO<sub>2</sub> but WG leads to higher viscosities than FA.

Sand used was clean river sand. Grain size ranged from 1.19 mm (#16 sieve) to 0.149 mm (#100 sieve). The ratio between sand and FA was 2.75 for the series of mixture varying sodium hydroxide concentration while it was 2.00 for the mixtures varying WG:NaOH ratio to obtain higher compressive strength. Mix proportions are summarized in Table 2. Symbols labelling the various mixtures in Table 2 are made up from Sand:FA ratio, WG:NaOH ratio and sodium hydroxide concentration, separated by a dash.

Symbol	FA	NaOH		WG	Sand	WG:NaOH ratio	Liquid:FA ratio	Sand:FA ratio
		Amount	Concentration					
2.75-0.0-10	23.5	11.8	10 M	0	64.7	0.0	0.50	2.75
2.75-0.0-12	23.5	11.8	12 M	0	64.7	0.0	0.50	2.75
2.75-0.0-14	23.5	11.8	14 M	0	64.7	0.0	0.50	2.75
2.75-0.0-16	23.5	11.8	16 M	0	64.7	0.0	0.50	2.75
2.75-0.0-18	23.5	11.8	18 M	0	64.7	0.0	0.50	2.75
2.00-0.0-18	28.6	14.3	18 M	0	57.1	0.0	0.50	2.00
2.00-0.5-18	28.6	9.5	18 M	4.8	57.1	0.5	0.50	2.00
2.00-1.0-18	28.6	7.2	18 M	7.2	57.1	1.0	0.50	2.00
2.00-1.5-18	28.6	5.7	18 M	8.6	57.1	1.5	0.50	2.00
2.00-2.0-18	28.6	4.8	18 M	9.6	57.1	2.0	0.50	2.00

Table 2 Composition of inorganic polymer samples (wt%)

## 2.2 Sample Preparation

The samples were mixed with a mortar mixer. FA was added to the mixer followed by NaOH solution. After five minutes, sand was added and then mixed for another five minutes. WG (if any) was added last and then mixed for five minutes more. After mixing, the fresh mixture was vibrated on a vibrating table for 15 seconds and then cast in 50×50×50 mm cubic moulds. Then the whole mould was wrapped with plastic sheet to prevent evaporation as much as possible. Samples were then separated into two groups: the first group was cured in an oven at 60°C for 48 hours then demoulded as recommended by Chaiyapoom et al [16]. The second group was cured under ambient conditions (typically 30°C) without any special treatment and then demoulded after 48 hours. All mixtures were left under ambient conditions after demoulding until tested. The compressive strength of each sample was measured after 7, 28, 60, and 90 days.

## 3. Results and Discussion

### 3.1 Compressive strength development of inorganic polymeric mortars without WG

Fig. 1 shows compressive strength development of the first series (cured at 60°C) for several sodium hydroxide concentrations. The compressive strength for all mixtures in this series increased similarly to traditional mortar made

from Portland cement [17]. The maximum compressive strength of samples in this group was 23.8 MPa from the 2.75-0.0-16 mixture of after 90 days.

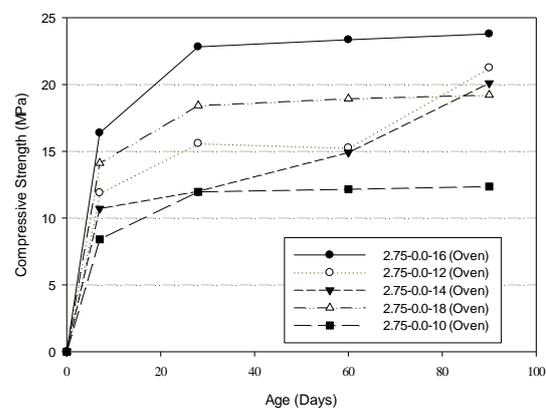


Fig. 1 Compressive strength development of oven-cured samples without WG

Fig. 2 shows the compressive strength development of the non-WG series cured under ambient conditions. It can be seen that compressive strength increases very slowly. However the strength does increase constantly. The 90-day compressive strength of all mixtures in this group was higher than 22.0 MPa, i.e. enough for normal concrete work [18]. The highest compressive strength in this group was 28.5 MPa from the 2.75-0.0-16 which higher than that of oven cured mortar of the same age. Every ambient cured sample showed a higher compressive strength compared to

the same mixture cured in an oven. Scanning electron microscope (SEM) images explained this phenomenon. There are many alumino-silicate particles on the surface of fly ash - see Fig. 3. These alumino-silicate compounds should combine and contribute to the compressive strength. However, evaporation and polycondensation of the oven cured samples occurred quickly. Thus the particles were starved of alkaline solution which is necessary for further polycondensation in later stages [19]. Therefore, alumino-silicate compound formation was hindered. Consequently, the compressive strength did not increase significantly after about 7 days.

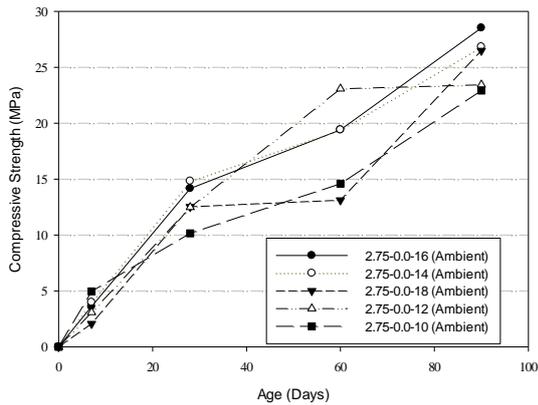


Fig. 2 Compressive strength development at ambient temperatures without WG

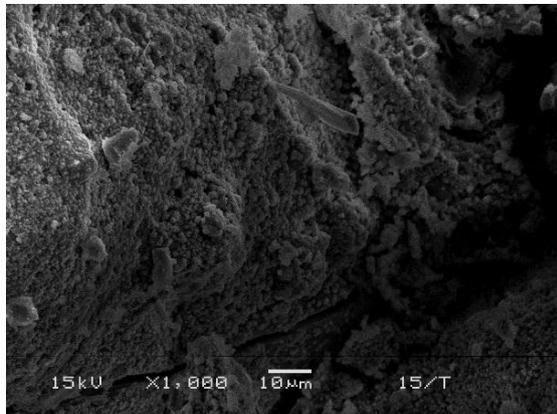


Fig. 3 SEM image of oven-cured 16M-mixture after 90 days

In Fig. 4 (same magnification as Fig. 3), we can see the different alumino-silicate development even though the mix proportion was the same. Due to the lower temperature, polycondensation proceeded slowly. This resulted in very low compressive strength in early stages as shown in Fig. 2. However, enough solution remained for further reaction. Additionally, the solutions evaporation rate was lower. Therefore, it is likely that the presence of solution allowed larger alumino-silicate polymers to form. Hence, the compressive strength increases as long as some solution remains.

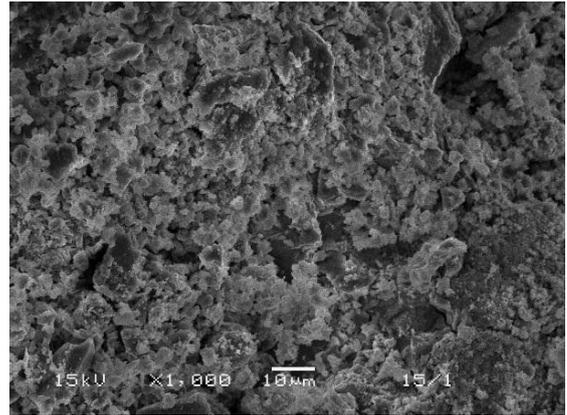


Fig. 4 SEM image of ambient-cured 16M-mixture at 90 days

### 3.2 Compressive strength development with WG

Fig. 5 shows that the compressive strength development of all samples in this group increased similarly to those in Fig. 1. However, a reduction in compressive strength was observed in most samples in this group. This decrease in compressive strength of inorganic polymers, especially geopolymer, has been reported previously [19-21]. This phenomenon decreases the confidence in using it as a building material. One factor that could cause the compressive strength reduction is WG content, because only the mixture that does not contain WG, 2.00-0.0-18, shows no decrease of compressive strength through the testing period. Normally, compressive strength of concrete-like material should not decrease in older samples. Moreover, it is not expected to increase after any decrease. Wongpa et al. reported that the polycondensation and cracking occurred simultaneously. When polycondensation occurs faster, compressive strength increases [19]. On the other hand, if cracking develops faster, the compressive strength reduction was observed [19]. This means that cracking might be observed between the ages of 28 and 60 days. However, due to the high viscosity of WG, evaporation of solution was reduced. Hence, the solution still remains and compressive strength increased due to polycondensation.

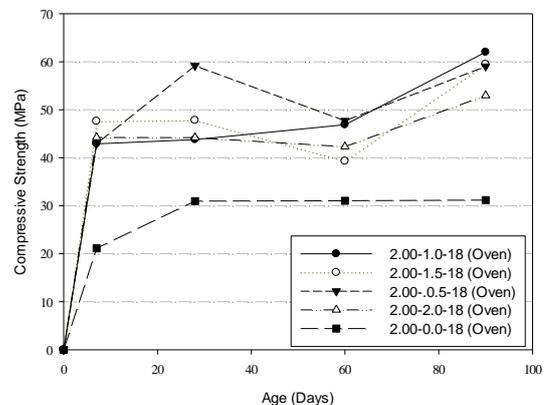


Fig. 5 Compressive strength development of oven cured samples containing WG

Fig. 6 shows the compressive strength development of inorganic polymeric mortar containing WG cured under ambient conditions. As expected, the compressive strength develops very slowly in the early stages and monotonically increases. This could be explained by the evaporation rate as discussed previously.

In both Fig. 5 and Fig. 6, we can see that some WG significantly increases the compressive strength of inorganic polymeric mortars. SEM images explain the polycondensation of the with-and-without WG mixtures. Fig 7 shows SEM images of the non-WG samples at 90 days for both oven-cured and ambient-cured samples. Observe that both samples show a similar pattern. Any amount of alumino-silicate with many pores could be observed. The compressive strength of both mixtures was similar - 31.2 MPa for oven-curing and 31.5 MPa for ambient-curing. Fig. 8 shows SEM images of the samples containing WG at 90 days. It was observed that with-WG samples are denser than those without WG. Thus the compressive strength of the with-WG sample was higher. Moreover, the oven-cured sample, Fig 8(a), is denser than that the ambient-cured one in Fig 8(b). Therefore, the compressive strength of 53.0 MPa of the oven-cured sample was higher than the 45.0 MPa of the ambient-cured one.

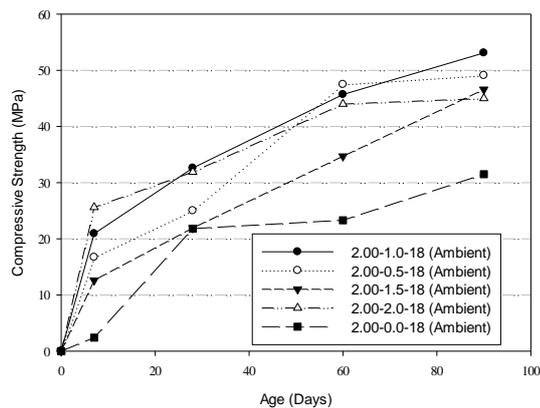


Fig. 6 Compressive strength development of ambient-cured samples containing WG

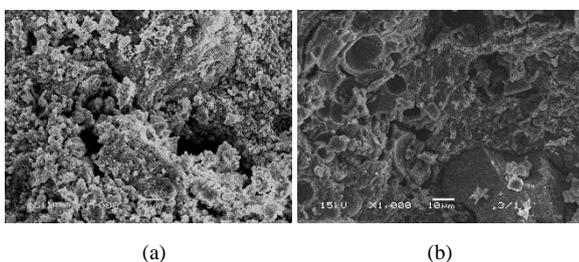


Fig. 7 SEM images of 2.0-0.0-18 mixture (a) oven-cured (b) ambient-cured

However, the compressive strength reduction was observed only in oven-cured samples. This implies that the WG is the key factor that controls the polycondensation of the inorganic polymer while the curing temperature controls

the pattern of development of the compressive strength. On the other hand, from the compressive drop, we inferred that 60°C curing resulted in cracking of mortar containing WG as observed previously [19].

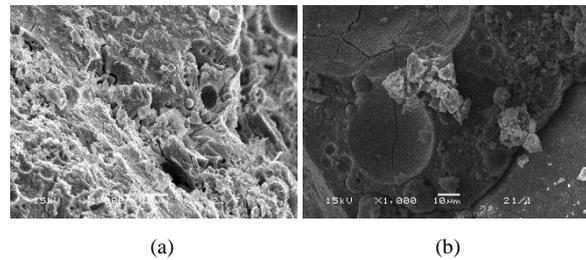


Fig. 8 SEM images of 2.0-2.0-18 mixture (a) oven-cured (b) ambient-cured

## 4. Conclusion

We conclude that water glass is the factor that controls both polycondensation and cracking in the inorganic polymer. The compressive strength reduction was observed only in samples containing water glass and cured at 60°C. Compressive strength of non-WG mixtures continued to develop and never dropped even at high curing temperature. For all low temperature cured samples, the compressive strength developed very slowly but continued to increase continuously for up to 90 days. Finally, we found that a maximum compressive strength of 62.0 MPa could be obtained from a mixture with WG cured at 60°C for 48 hours. However, without water glass and cured under ambient condition, the maximum compressive strength of 31.5 MPa was observed - sufficient for normal concrete work.

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