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# ENGINEERING PROPERTIES OF HIGH VOLUME SLAG CEMENT GROUT IN TROPICAL CLIMATE

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**Abstract:** Concrete repair is a complex process. It must successfully integrate new material with the old one to form a lasting composite that can withstand harsh environment. Cement based grout is used for most general repair works due to its low cost and availability. This research, however, used ordinary Portland cement and ground granulated blast furnace slag (GGBFS) as binders to produce a slag cement based grout. The research objective is to produce a sufficient mix proportion for slag cement based grout that has good engineering properties and can be used as concrete repair material in tropical climates. Flow cone test was used to determine the mix proportions of cement grout. Several batches of 50% slag replacement cement mixes were designed and tested for its flowability and compressive strength properties. Finally, the mix proportion with fresh properties, namely workability, bleeding, and setting time that fulfill the requirements of ASTM C 937 and has optimum strength development was selected. The optimum compressive strength obtained for 50% slag replacement cement grout was above 30 MPa and its flexural strength was above 9 MPa under water curing condition. Result of drying shrinkage test strengthened the finding that the replacement of 50% slag as binder to cement mix with proper mix proportion is suitable to be used in normal grade concrete repairs under tropical climate.

**Keywords:** *Slag; Compressive strength; Flexural strength; Drying shrinkage*

**Abstrak:** Pembaikan konkrit adalah satu proses yang kompleks. Ia mestilah mampu menggabungkan bahan-bahan baru dengan bahan-bahan lama bagi membentuk komposit yang tahan dengan keadaan persekitaran yang melampau. Simen grout diguna untuk kebanyakan kerja-kerja pembaikan biasa kerana kosnya yang rendah dan senang didapati. Penyelidikan ini menggunakan Portland simen biasa dan slag kisar halus relau bagas (GGBFS) sebagai bahan pelekat untuk menghasilkan simen grout. Objektif kajian ini ialah untuk menghasilkan campuran simen grout yang sesuai di samping mempunyai sifat-sifat kejuruteraan yang baik sebagai bahan kerja pembaikan konkrit di bawah cuaca tropika. Campuran yang sesuai ditentukan secara pencampuran cubaan dan diikuti dengan ujian pengaliran. Beberapa bancuhan yang menggunakan penggantian 50% slag kepada bancuhan simen telah direka dan diuji sifat pengaliran dan kekuatan mampatannya. Akhirnya, campuran yang mempunyai sifat-sifat basah seperti kebolehkerjaan, lelehan air dan masa pengerasan yang dapat menepati permintaan ASTM

C 937 dan pencapaian kekuatan yang optimum telah dipilih. Kekuatan mampatan optimum untuk 50% gantian slag kepada simen grout di bawah keadaan pengawetan dalam air adalah melebihi 30 MPa manakala kekuatan lenturannya melebihi 9 MPa. Keputusan ini disokong oleh ujian pengecutan kering yang juga membuktikan bahawa penggantian 50% slag sebagai bahan simen untuk campuran simen dengan rekaan yang tepat adalah sesuai bagi kerja pembaikan konkrit gred biasa di bawah cuaca tropika.

**Kata Kunci:** *Slag; Kekuatan mampatan; Kekuatan lenturan; Pengecutan kering*

## 1.0 Introduction

Cracking of reinforced concrete elements might be caused by several factors such as design false, overloading, improper construction and curing and seasonal temperature variations. Repair of concrete cracks should be carried out to make sure the cracking elements could function properly.

Grout is one of the materials that is economical and compatible for repairing structural cracks. Grouting technique started 200 years ago by a French engineer, Charles Berrgny who inspired the idea to repair the structure damages of harbor of Dieppa by grouting using percussion pump invented by him in year 1802 (Bowen, 1981; Nonveiller, 1989). Later, in England, Marc Isambard Brunel used Portland cement as cement grouting materials in 1838 during the construction of the first Thames tunnel at Wapping. Then, cement grouting becomes widely used in the early part of the last century (Bowen, 1981). Nowadays, all types of grout are used including cement, cement and sand, clay-cement, slag-cement, resin gypsum-cement, clays asphalt, pulverized fuel ash and a large number of colloid and low viscosity chemicals. Nonveiller (1989) define grouting as a procedure of injecting the grout materials into fissures and cracks in order to enhance their properties and reduce the deformations.

Ground granulated blast furnace slag (GGBFS) cement is hydraulic cement produced during the reduction of iron ore to iron in a blast furnace. Molten slag is tapped from a blast furnace, rapidly quenched with water (granulated), dried and ground to a fine powder. The rapid quenching “freezes” the molten slag in a glassy state, which gives the product its cementitious properties and become one of the most popular cementitious materials used in concrete (ACI 233R, 1995). Currently, slag cement is used to produce blended cement that complies with ASTM C 595 (1992). Slag cement can be used as a constituent in hydraulic cements produced under ASTM C 1157 (1992).

The cost and compatibility of the repairing materials are significant factors to be considered in repairing works. This research aimed at producing economical and good performance slag cement based grout materials for structural repair purposes. The study concentrates mainly on producing a mix proportion developed using slag cement based grout and later, the significant engineering properties such as flowabilty, setting time, compressive strength and durability under tropical climate of the grout were tested and discussed.

## 2.0 Material and Methods

The production of the grout is based on ground granulated blast furnace slag (GGBFS) and ordinary Portland cement (OPC) as binder, and fine oven dried sand as filler. Superplasticizer (SP) was used to enhance workability and for early age strength development. Table 1 shows the physical properties and chemical constituents of GGBFS and OPC used in this study.

Table 1: Physical and Chemical properties of OPC and GGBFS

| Chemical Constituents | OPC (%) | GGBFS (%) |
|---|---|---|
| Silicon dioxide ($SiO_2$) | 20.1 | 28.2 |
| Aluminium oxide ($Al_2O_3$) | 4.9 | 10.0 |
| Ferric oxide ($Fe_2O_3$) | 2.5 | 1.8 |
| Calcium oxide (CaO) | 65.0 | 50.4 |
| Magnesium oxide (MgO) | 3.1 | 4.6 |
| Sulphur oxide ($SO_3$) | 2.3 | 2.2 |
| Sodium oxide ($Na_2O$) | 0.2 | 0.1 |
| Potassium oxide ($K_2O$) | 0.4 | 0.6 |
| Titanium oxide ($TiO_2$) | 0.2 | - |
| Phosphorous oxide ($P_2O_2$) | <0.9 | - |
| Carbon content (C) | - | - |
| **Physical Properties** | | |
| Specific gravity | 3.2 | N.A |
| Loss on ignition (LOI) | 2.4 | 0.2 |
| Fineness (% passing 45μm) | 93.0 | 100 |

Source: Manager, Slag Cement (Southern) Sdn. Bhd., YTL (Pers. Communication)

The cement grout was prepared by weighing OPC, GGBFS and graded dry sand according to mix proportions and then mixed them in a clean, dry concrete mixer for three minutes until all the materials blended intimately and uniformly. Weighted clean tap water was later added into the dry mix. The grout was then mixed for about three minutes in concrete mixer until uniformity was achieved.

First, the optimum 50% slag cement based grout was selected from trial mixes in which the grout must be flowable with bleed water less than 2% of the total volume of the grout and the compressive strength of more than 30 MPa. Then the significant engineering properties of selected 50% slag cement based grout were investigated.

According to ASTM C 827 (1987), to produce the fluid mixture using flow cone method, the time of efflux of the fluid grouts shall range from 10 to 30 seconds. In this study, the times of efflux of the fluid grouts were in accordance to ASTM C 937 (2002) standard which shall fall within $21 \pm 2$ seconds. The fresh mixed grouts were tested for bleeding and combined expansion (grout plus bleed water) and expansion after 3 hours complied with the standard test method 98a in ASTM C 940 (2003). The results shall comply with the requirement of ASTM C 937 (ASTM C 937, 2002). Initial and final setting times of cementitious grout were investigated using Vicat needle test according to ASTM C 953 (1987).

The density of specimen was determined in accordance to RILEM CPC10.2 (1994) while compressive strength tests were carried out based on Part 116 of BS 1881 (1993). The flexural strength test was carried out in accordance to ASTM C 78 - 84 (ASTM C 78, 1988). Prisms with size100 x 100 x 300 mm according to RILEM CPC9 (1994) were cast to determine drying shrinkage and test results should comply with RILEM AAC5.1 (1994).

### *2.1 Slag Activity Index*

The slag activity index test was based on ASTM C 989 – 89 (ASTM C 989, 1989), and the value was calculated using formula given in ASTM C 989 to determine the grade of GGBFS used. Based on Table 2, slag activity index was calculated as follow:-

Slag activity index, % $=(fcu_s / fcu_o) \times 100\%$ (1)

where $fcu_s$ is compressive strength of 50% slag cement based mixes, $fcu_o$ is compressive strength of plain ordinary Portland cement based mixes.

Table 2: Compressive strength of 50% slag cement based mixes and 100 % ordinary Portland cement mixes

| Type of mixes | Average Ultimate Load (kN) | | Average Compressive Strength (MPa) | |
|---|---|---|---|---|
| | 7 days | 28 days | 7 days | 28 days |
| 50% slag cement | 108.63 | 181.10 | 21.80 | 36.34 |
| 100% OPC | 146.00 | 184.40 | 29.29 | 37.00 |

### *2.2 Curing Conditions*

The curing conditions adopted in this study is described as follows:-

i. Continuous water curing at $26^0$C.
ii. Air curing in laboratory. Average temperature at $30^0$C with 65% relative humidity.
iii. Tropical climate outside laboratory. Temperature ranged from $26^0$C (rainy day) to $38^0$C (hot day) with humidity ranges from 25% (hot and dry) to 90% (wet).

## 3.0 Results and Discussion

The following test results are discussed based on fresh and hardened properties of 50 % slag replacement mix.

### *3.1 Fresh Properties Results*

This section discusses test results on flowability/workability, bleeding, expansion and setting time.

#### *3.1.1 Flowabilty/ Workability*

Table 3 shows the workability of freshly mixed 50% slag replacement cement grout with binder to sand ratios of 1:1, 1:2 and 1:3. The results show that with 1:1 binder:sand (b:s) proportion for M-50 mix has performed good workability with lower water binder ratio compared to other mixes. The higher binder:sand ratios were due to higher water content to maintain its workability. Addition of 0.1% superplasticizer slightly reduced water binder ratio from 0.01 to 0.02 for M-50 with 1:1 binder:sand proportion to obtain similar workability based on flow cone test but has no effect on workability for the same mix with 1:2 binder:sand proportion.

Table 3 : Water to binder ratio of 50 % slag replacement cement grout

| Mix Ingredients | By weight | | | | |
|---|---|---|---|---|---|
| | M-50 | | | | |
| Binder:Sand Ratio | 1:1 | 1:1 | 1:2 | 1:2 | 1:3 |
| OPC (%) | 50 | | | | |
| Superplasticizer (%) | - | 0.1 | - | 0.1 | - |
| Water:Binder Ratio | 0.58 to 0.59 | 0.56 to 0.57 | 0.76 to 0.77 | 0.76 to 0.77 | 1.02 to 1.04 |

#### *3.1.2 Bleeding and Expansion*

Table 4 : Percentage of bleeding, combined expansion and volume change of 50% slag replacement cement grout

| Type of Results | M-50 | | | | |
|---|---|---|---|---|---|
| Binder:Sand Ratio | 1:1 | 1:1 | 1:2 | 1:2 | 1:3 |
| Superplasticizer (%) | - | 0.1 | - | 0.1 | - |
| Combined Expansion (%) | | | | | |
| (From start until end, 3 hours) | 0 | 0 | 0 | 0 | 0 |
| Expansion/ Volume Changed (%) | | | | | |
| After 3 hours | -1.38 | -1.38 | -2.63 | -3.13 | -2.99 |
| Bleeding at prescribed interval (%) | | | | | |
| 15 minutes | 0.24 | 0.25 | 1.00 | 1.25 | 1.12 |
| 30 minutes | 1.23 | 1.25 | 1.25 | 2.50 | 1.74 |
| 45 minutes | 1.23 | 1.25 | 1.88 | 2.75 | 2.61 |
| 1 hour | 1.38 | 1.38 | 2.50 | 3.13 | 2.99 |
| 1.5 - 3 hrs | 1.38 | 1.38 | 2.63 | 3.13 | 2.99 |
| Final bleeding (%) | 1.38<2 | 1.38<2 | 2.56>2 | 3.13>2 | 2.92>2 |

Table 4 shows the percentage of combined expansion (grout plus bleed water), expansion and bleeding at prescribed interval and final bleeding for each batch of freshly mixed 50% slag replacement cement grout as determined using test 98a in ASTM C 940 (2002). The test results showed that no combined expansion for each batch of freshly mixed slag cement based grout but the volume of grout was slightly reduced. The reduction in volume is due to some loss of water via bleed and filtration at the early stage. Addition of 0.1% superplasticizer has no effect on bleeding of M-50 with 1:1 binder:sand ratio but slightly increase the percentage of bleed water about 0.5% for the same mix with 1:2 binder:sand ratio. It was observed that by increasing the sand content for cement grout mixes has caused the percentage of bleed water to increase. The results from Table 4 also showed that for 50 % slag replacement cement grout with 1:1 binder:sand ratio, the percentage of final bleeding did not exceed 2%, and thus fulfill the requirement of ASTM C 937 – 02 (ASTM C 937, 2002). However, the final bleed water of slag cement grout with 1:2 and 1:3 binder sand ratios have exceeded 2%, which did not fulfill the ASTM C 937 – 02 requirement. The excessive bleeding of freshly placed mix can result in problems with finishing and a weak surface layer particularly on flat slabs, a reduction in the bond between the steel and the concrete and an increase risk of the occurrence of plastic settlement cracks.

### *3.1.3 Setting Time*

ASTM C 403 (ASTM C 403, 2001) identifies initial and final setting time of set as penetration resistance. For initial setting time, penetration resistance value should reach 500 psi (3.5 $N/mm^2$) while for final setting time, penetration resistance value is 4000 psi (27.6 $N/mm^2$) (ASTM C 403, 2001). The hydration process combines cement and water forming C-S-H gel, gradually changing the mix from a plastic, moldable stage to a solid capable of withstanding substantial loads. The final setting time is the time when the concrete completely hardened. Initial set time is important to give the indication and estimation to contractor the tolerance of time to deliver and apply the mix. Contractors normally remove the formwork based on the final setting time of concrete. The lower the ambient and/ or concrete temperatures, the slower the set times will be. Slower times of set are beneficial in hot weather because the contractor has a longer time to deliver, place, and finish the concrete. The results obtained from Vicat needle test showed that for 50% slag replacement cement grout, the initial setting time is around 3 hours 30 minutes while the final setting time is more than 5 hours. The results showed that there is sufficient time to deliver, apply and finish the slag cement grout under tropical climate.

## *3.2 Hardened Properties Results*

This section discusses test results on compressive strength, flexural strength, drying shrinkage and swelling.

### *3.2.1 Compressive Strength*

Table 5 presents the average ultimate load and compressive strength for each batch of grout at 7, 14 and 28 days. When the Portland cement is mixed with water, the hydration process of cement starts which results in the formation of calcium silicate hydrate (C-S-H) and calcium hydroxide ($Ca(OH)_2$). C-S-H is a crystal that contributed to the strength gain and cohesion to grout mix while the $Ca(OH)_2$ is a by-product that does not contribute any strength. However, the silica content of GGBFS when acted with water and $Ca(OH)_2$, additional C-S-H molecules are formed and thus brought more strength to the grout mix. Addition of 0.1% superplasticizer has slightly decreased the water binder ratio and increased the strength of grout mix as compared to the mix without superplasticizer. When the grout mix has lower binder to sand ratio, more water is needed to maintain the workability of cement grout. The excessive water inside the samples may weaken the bonding between cement particle and sand and hence reduce the strength of the grout.

Table 5 : Compressive strength of 50% slag replacement cement grout cubes with different binder:sand ratio under water curing condition

| Type of Mix | Binder:Sand Ratio | Density ($kg/m^3$) | | Compressive Strength (MPa) | | |
|---|---|---|---|---|---|---|
| | | Wet | Dry | 7 Days | 14 Days | 28 Days |
| M-50 (50% Slag) | 1:1 | 2072 | 2066 | 21.8 | 30.1 | 36.3 |
| | 1:1 (with 0.1% SP) | 2100 | 2094 | 28.5 | 35.5 | 41.6 |
| | 1:2 | 2086 | 2078 | 16.0 | 21.1 | 28.6 |
| | 1:2 (with 0.1% SP) | 2109 | 2103 | 19.2 | 24.3 | 30.5 |
| | 1:3 | 2063 | 2057 | 14.9 | 18.0 | 23.3 |

Table 5 and Figure 1 show that the compressive strength for 50% slag cement grout with 1:1 binder to sand ratio has achieved more than 35 MPa after 28 days under water curing condition. While the compressive strength for M-50 grout mix with 1:2 binder to sand ratio is around 30 MPa and slightly increase when 0.1% superplasticizer was added, the bleeding was more than 2.5% (refer to Table 3). The compressive strength of M-50 grout mix with 1:3 b:s ratio is around 23 MPa but the bleeding has increased to more than 3%. The overall results indicated that M-50 grout with 1:1 b:s ratio (with or without superplasticizer, depending on the strength required) is the best choice among the grout mixes produced.

The compressive strengths for each batch of 50% slag replacement cement grout with 1:1 b:s ratio under different curing conditions at 7, 14 and 28 days are shown in Figure 2. The results indicate that the 7-day strength of samples under air curing condition is higher than the samples under water or natural weather curing conditions because the higher temperature had accelerated the hydration process at the initial stage. At the later ages of 14 days and 28 days periods, the water cured samples showed a higher compressive strength as compared to the other two curing conditions.

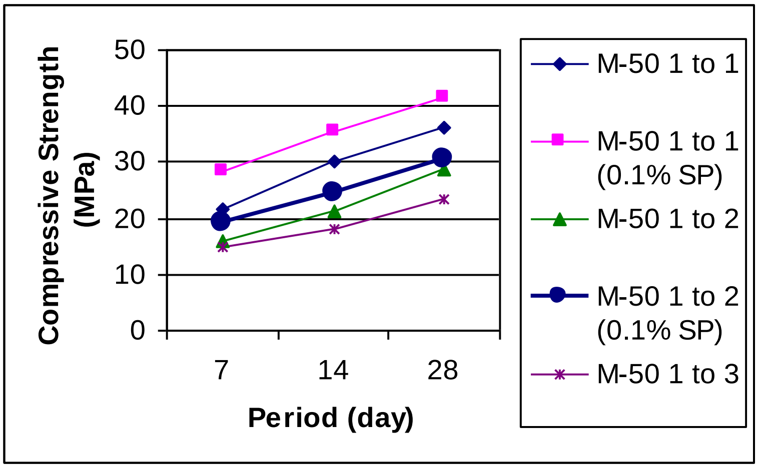


Figure 1 : Compressive strength of 50% slag replacement cement grout with different binder to sand ratio under water curing condition

The water cured samples have sufficient water for further hydration process at the mentioned ages as compared to samples under air and natural weather. The samples were facing the evaporation through diffusion or capillary inside samples due to the hot weather causing insufficient water content for complete hydration process.

According to Bungey and Millard (1996), under dry condition, water will be absorbed to the sides of pore and once the pore walls have reached their absorption limit, water will diffuse across the pores and evaporate. The evaporation from air cured samples can be noticed by its lighter density as compared to density of water cured samples. For natural weather cured specimens, the strength and density totally depend on temperature and humidity of the surrounding air. Initial water curing is important to improve the strength of slag cement or cement-based grout.

As shown in Figure 2, M-50 achieved strength above 30 MPa at 28 days under all curing conditions. Figure 3 shows the long-term strength development of M-50. It's evident that 50% slag replacement cement grout has consistent strength development up to 9 months under water curing condition. The strength of M-50 decreased under air curing condition due to evaporation of water absorbed by pore wall through capillary diffusion but still can achieve the compressive strength above 30 MPa up to 9 months. For natural weather cured samples, the results showed that the strength development up to 9 months is better than air-cured but lower than water-cured samples. The strength development of samples under tropical climate depends on the relative humidity and temperature which vary considerably. It seems that the specimens being cured under inconsistent wet-dry cycles, which is considered as severe condition as shown in Figure 3 the M-50 samples still can achieve strength of more than 35 MPa under all curing conditions up to 9 months and this can be considered durable under tropical climate. However, for air-cured samples, further tests should be carried out for a longer period of exposure.

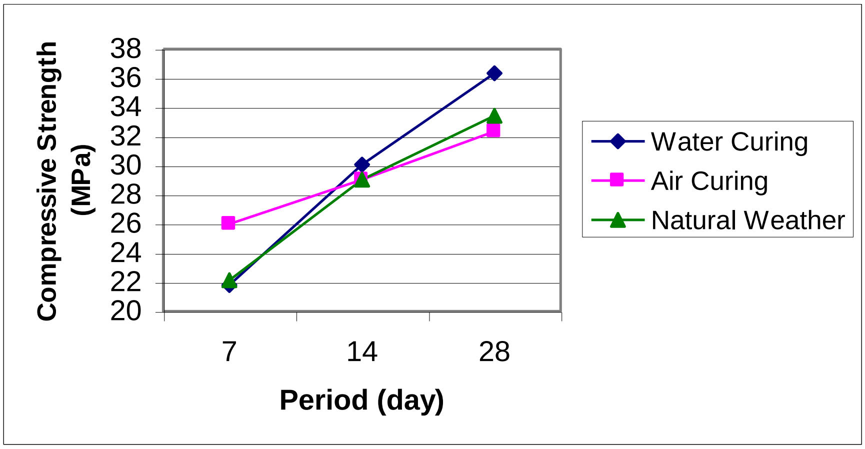


Figure 2: Short-term compressive strength of 50% slag replacement cement grout under different curing conditions

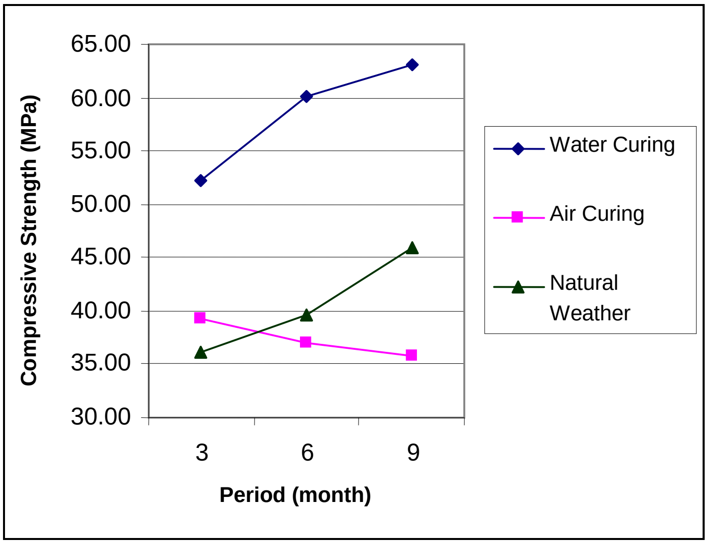


Figure 3 : Long-term compressive strength of 50% slag replacement cement grout under different curing conditions

### *3.2.2 Flexural Strength*

Figure 4 shows that M-50 has higher flexural strength than M-CTR under water curing condition but vice versa for air and natural weather curing. M-50 achieved 9.4 MPa at 6 months period under water curing condition. It showed that moist curing condition could provide higher strength development to slag cement based mixes compared to other conditions. M-50 has lower flexural strength under natural weather and air curing conditions because of insufficient water content for long-term hydration process due to pozzolanic activity between slag and $Ca(OH)_2$. When slag cement is used in grout mixes, early strength development may be slower, as GGBFS is finer than OPC, the slag cement based mixes need more water for ultimate strength development in long-term period as compared to plain OPC mix. The loss of water needed inside samples under air and natural weather conditions affected the ultimate strength development of slag cement based grout. Slag cement has a significant effect on the flexural strength of concrete. Improved flexural strengths are attributed to the increased denseness of the paste and improved paste-aggregate bond.

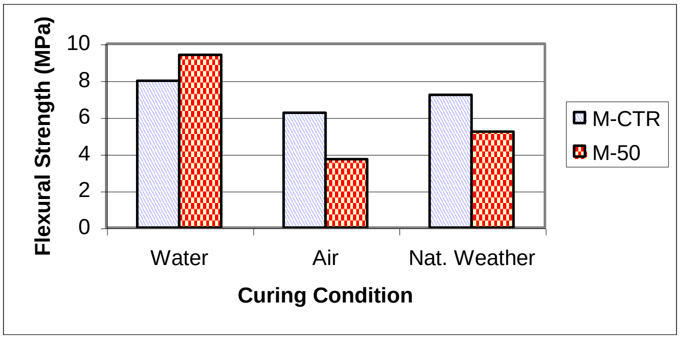


Figure 4 : 6-months flexural strength of 50% slag replacement cement grout compared to control mix under different curing conditions

### *3.2.3 Drying Shrinkage and Swelling*

The drying shrinkage or swelling results from all curing conditions are presented in Figures 5 to 7. Figure 5 indicates that for M-50, the total average drying shrinkage is lower than the control specimen (M-CTR) under air condition. On the other hand, in the case of water curing condition (Figure 6), the control specimens showed some shrinkage but M-50 specimens were swelling slightly. However, both mixes were swelling for natural weathering condition as illustrated in Figure 7. The average swelling value of M-50 is lower than control mix under natural weather condition. Based on the current investigation, it can be concluded that 50% of the OPC can be beneficially replaced with GGBFS to reduce the average drying shrinkage (air curing condition) or swelling (natural weather) and maintain the stability of grout material.

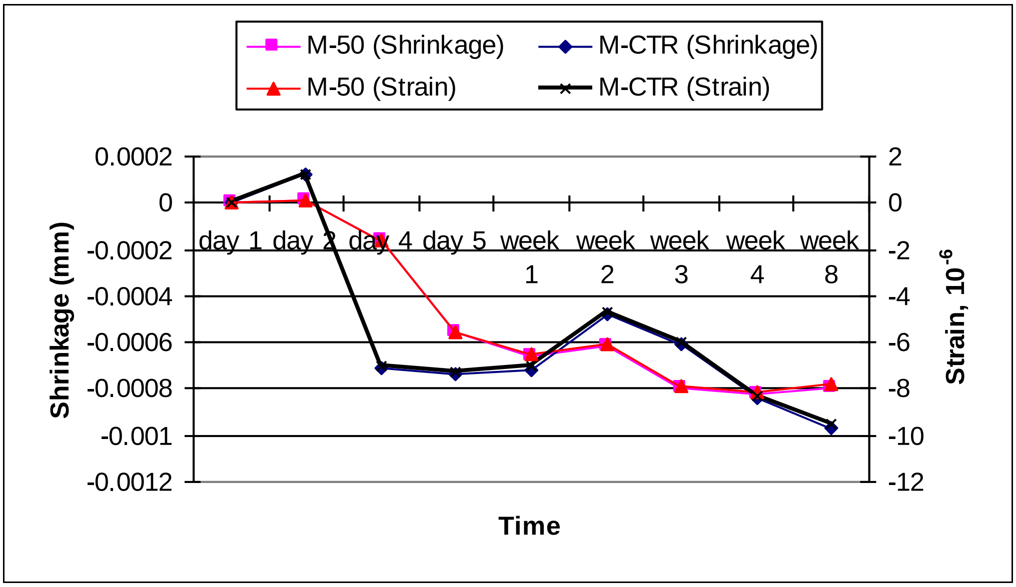


Figure. 5: Average shrinkage and swelling of 50% slag replacement cement grout as compared to control mix under air curing condition

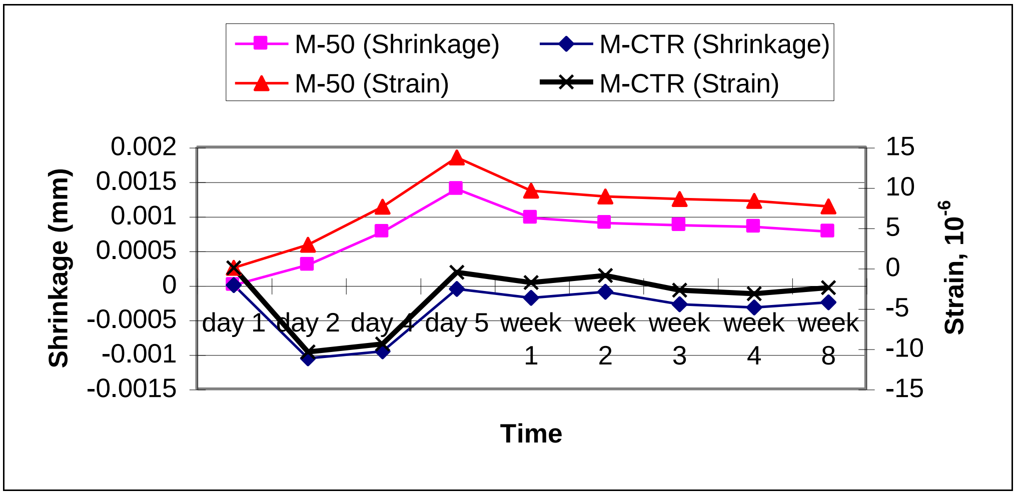


Figure 6 : Average shrinkage and swelling of 50% slag replacement cement grout as compared to control mix under water curing condition

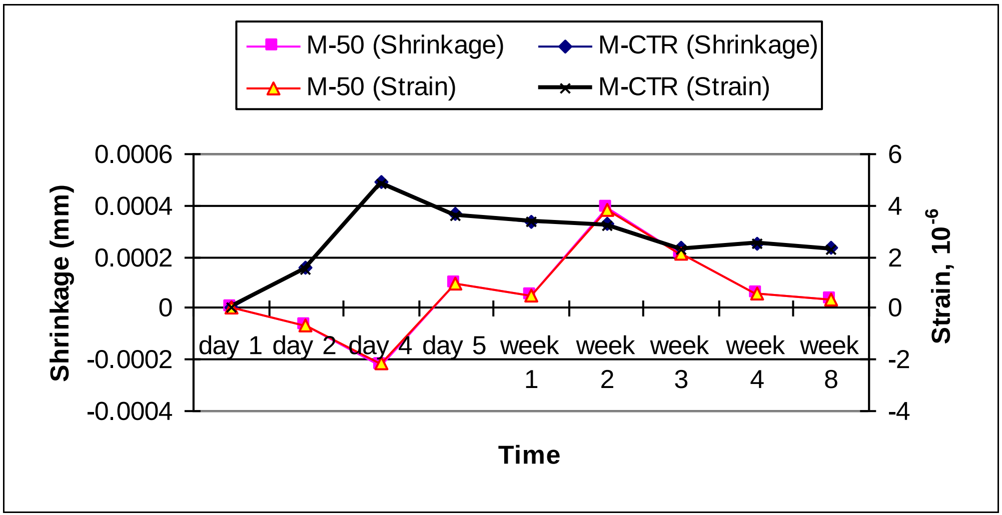


Figure 7 : Average shrinkage and swelling of 50% slag replacement cement grout as compared to control mix under natural weather

## 4.0 Conclusions

The present investigation found that the most suitable binder to sand ratio for 50% slag replacement cement grout (M-50) is 1 to 1, while the best water to binder ratio ranges from 0.58 to 0.60 in order to maintain good workability and required strength development. The properties of fresh mix M-50 fulfilled the requirement of ASTM C 937 and ASTM C 938. The compressive strength test results achieved 30 MPa at 28 days under all curing conditions, which is compatible to normal concrete grade used for building construction in Malaysia of above 30 MPa at 28 days under all curing conditions. The average flexural strength of M-50 prisms is in the range of 18% to 20% of the corresponding compressive strength. Drying shrinkage and swelling behaviors of M-50 slag cement grout are within the acceptable range, from 0 to 10 microstrains, compared to normal weight concrete which shrinks from 400 to 800 microstrains (Peter, 1994).In fact it behaves better than the control mix without slag addition.

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