FINAL REPORT ON DURABILITY AND STRENGTH DEVELOPMENT OF GROUND GRANULATED BLASTFURNACE SLAG CONCRETE

GEO REPORT No. 258

Peter W.C. Leung & H.D. Wong

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CIVIL ENGINEERING AND DEVELOPMENT DEPARTMENT

THE GOVERNMENT OF THE HONG KONG SPECIAL ADMINISTRATIVE REGION

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PREFACE

In keeping with our policy of releasing information which may be of general interest to the geotechnical profession and the public, we make available selected internal reports in a series of publications termed the GEO Report series. The GEO Reports can be downloaded from the website of the Civil Engineering and Development Department (http://www.cedd.gov.hk) on the Internet. Printed copies are also available for some GEO Reports. For printed copies, a charge is made to cover the cost of printing.

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R.K.S. Chan
Head, Geotechnical Engineering Office
January 2011

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FOREWORD

With the support of the Standing Committee on Concrete Technology (SCCT), the Public Works Central Laboratory (PWCL) carried out an investigation on the strength development and durability of Ground Granulated Blastfurnace Slag (GGBS) concrete. The investigation studied the characteristics of concrete with different percentages of GGBS and compared them with that of Portland Cement concrete. The effects of silica fume, source of GGBS, curing environments and curing durations were also examined.

This final report presents the study findings for concrete cubes with an age of up to 364 days.

Mr Peter W.C. Leung prepared this report in conjunction with Mr H.D. Wong. Mr Paul Y.T. Yuen organized and supervised the testing work with the assistance of Mr Raymond C.T. Kwok, Mr Bosco W.C. Lee and Mr H.Y. Pang of the PWCL. Members of the SCCT and its Consultative Committee have provided useful comments on the draft report. All contributions are gratefully acknowledged.

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1. INTRODUCTION

The blastfurnace slag is a by-product of the iron manufacturing industry. Iron ore, coke and limestone are fed into the furnace and the resulting molten slag floats above the molten iron at a temperature of about 1500°C to 1600°C. The molten slag has a composition of about 30% to 40% SiO_2 and about 40% CaO, which is close to the chemical composition of Portland cement. After the molten iron is tapped off, the remaining molten slag, which consists of mainly siliceous and aluminous residue (Higgins, 2007) is then water-quenched rapidly, resulting in the formation of a glassy granulate. This glassy granulate is dried and ground to the required size (Hooton, 2000), which is known as ground granulated blastfurnace slag (GGBS).

The production of GGBS requires little additional energy as compared with the energy needed for the production of Portland cement. The replacement of Portland cement with GGBS will lead to significant reduction of carbon dioxide gas emission. GGBS is therefore an environmentally friendly construction material. It can be used to replace as much as 80% of the Portland cement used in concrete.

GGBS concrete has better water impermeability characteristics as well as improved resistance to corrosion and sulphate attack. As a result, the service life of a structure is enhanced and the maintenance cost reduced.

In view of the potential advantages of using GGBS, the Standing Committee on Concrete Technology (SCCT) endorsed in 2008 the proposal by the Public Works Central Laboratory (PWCL) to conduct a research study to investigate the strength development and durability of GGBS concrete. The main aim of the study is to compare the performance of concrete containing various proportions of GGBS. The influence of silica fume and the sources of GGBS were also studied. In September 2009, an interim report containing the findings of laboratory tests on concrete cubes up to an age of 91 days was issued (Leung et al, 2009).

This final report presents the study results up to about one year.

2. LITERATURE REVIEW

2.1 Experience of Using GGBS in Concrete

The hydraulic potential of blastfurnace slag was first discovered in Germany in 1862. In 1865, lime-activated blastfurnace slag started to be produced commercially in Germany and in 1880 GGBS was first used in combination with Portland cement (Concrete Society, 1991). In Europe, GGBS has been used for over 100 years. In North America, the history of the use of GGBS in quality concrete dates back about 50 years (Yazdani, 2002). In Southeast Asian countries including Mainland China and Hong Kong, GGBS was used in concrete in around 1990. Between 1955 and 1995, about 1.1 billion tonnes of cement was produced in Germany, about 150 million tonnes of which consisted of blastfurnace slag (Geiseler et al, 1995). In China, the estimated total GGBS production was about 100 million tonnes in 2007 (Chen, 2006).

GGBS has been widely used as a partial replacement of Portland cement in

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construction projects. In Western Europe, the amount of GGBS used accounts for about 20% of the total cement consumed, whereas in the Netherlands it accounts for 60% of the total cement consumption (Tsinghua University, 2004).

There are abundant examples of the use of GGBS concrete in construction projects. In New York, the concrete used in the construction of the World Trade Centre has about 40% GGBS replacement (Slag Cement Association, 2005). At the Minneapolis Airport, the airfield pavements were constructed using concrete with 35% GGBS replacement. Other projects using GGBS include the world's largest aquarium - the Atlanta's Georgia Aquarium which used 20% to 70% GGBS replacement. The Detroit Metro Airport Terminal Expansion used concrete with 30% GGBS replacement. The Air Train linking New York's John F. Kennedy International Airport with Long Island Rail Road trains used concrete with 20% to 30% GGBS replacement.

In China, GGBS has been widely used in major construction projects such as the Three Gorges Dam, Beijing-Shanghai Express Rail, and Cross-bay Bridge of Hangzhou Bay. The GGBS replacement level is generally around 40% (China Cements, 2009; ChinaBiz, 2009).

In Hong Kong, GGBS was used in the construction of the Tsing Ma Bridge, which requires a design life of 120 years. For this project, the GGBS replacement levels were from 59% to about 65%, with a maximum water/(cement+GGBS+silica fume) ratio of about 0.39. GGBS was also used in the construction of the Stonecutter Island Bridge with GGBS replacement of between 60% and 70%.

For reinforced concrete in a marine environment, the SCCT endorsed in year 2000 a specification, which allows the use of GGBS. The specified replacement level for normal application is in the range of 60% to 75% by mass of the cementitious content whilst for low heat applications it ranges from 60% to 90% (Standing Committee on Concrete Technology, 2000).

2.2 Benefits of Using GGBS in Concrete

2.2.1 Sustainability

It has been reported that the manufacture of one tonne of Portland cement would require about 1.5 tonnes of mineral extractions together with 5000 MJ of energy, and would generate about 0.95 tonne of CO_2 equivalent (Higgins, 2007).

As GGBS is a by-product of the iron manufacturing industry, Higgins (op cit) also reported that the production of one tonne of GGBS would only generate about 0.07 tonne of CO_2 equivalent and consume about 1300 MJ of energy.

According to Higgins (op cit), GGBS scores 0.47 Ecopoints, whereas Portland cement scores 4.6, which means GGBS would only bring about one-tenth of that of Portland cement in terms of environmental impact.

In China, it has been reported that a GGBS manufacturer in Xi'an produced about 1.2 million tonnes of GGBS in year 2008, which could help to reduce about 1.2 million tonnes of CO_2 equivalent emissions, 1.1 million tonnes of coal consumption and 1.7 million tonnes of

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mineral extraction. There are obvious environmental benefits by making full use of the slag (ChinaBiz, 2009).

2.2.2 Concrete with Improved Durability

It is generally known that GGBS can improve the durability of a concrete structure by reducing the water permeability, increasing the corrosion resistance and increasing the sulphate resistance. The improved properties can extend the service life of structures and reduce the overall maintenance costs. Based on a life cycle prediction model, the service life of a Maryland bridge deck was estimated to have increased from 38 years to 75 years with the use of concrete incorporating 40% GGBS replacement (Slag Cement Association, 2005).

2.3 Physical Properties

2.3.1 Particle Size

The BS EN 15167-1 requires that the minimum specific surface area of GGBS shall be 2750 cm^2/g (BS EN 15167-1:2006). In China, GGBS is classified in three grades, namely S75, S95 and S105. The GB/T18046 requires a minimum surface area of 3000 cm^2/g for grade S75 GGBS, 4000 cm^2/g for grade S95, and 5000 cm^2/g for grade S105, which are higher than the BS EN's requirements (GB/T18046-2008). It has been reported that slag with a specific surface area between 4000 cm^2/g and 6000 cm^2/g would significantly improve the performance of GGBS concretes (北京首鋼嘉華建材有限公司, 2004).

Both BS EN 15167-1 and GB/T18046 adopt a requirement on the specific surface area rather than the particle size of GGBS. Some researchers reported that the reactivity of GGBS would be improved when the particle size was less than 45 μm. They suggested that less than 2% of the GGBS particles should be retained on the 45 μm sieve and that the specific surface area shall be greater than 4200 cm^2/g (e.g. 北京市高強混凝土有限責任公司, 2004).

2.3.2 Density

There are no specific requirements in BS EN 15167-1 on the density of Portland cement and GGBS. GB/T18046 requires the relative density of GGBS to be not less than 2.85 (GB/T18046-2008). The Concrete Society (1991) reported that the relative density of GGBS was about 2.9 as compared to 3.15 for Portland cement. The inclusion of GGBS in a concrete mix as an equal mass replacement for Portland cement would cause a slight increase in the total volume of the cementitious content.

2.3.3 Colour

GGBS powder is almost white in colour in the dry state as shown in Figure 1. Fresh GGBS concrete may show mottled green or bluish-green areas on the surface mainly due to the presence of a small amount of sulphide. This colour fades subsequently after casting, as

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the sulphide decomposes in air to form hydrogen sulphide (Slag Cement Association, 2005).

2.4 Chemical Properties

2.4.1 Chemical Composition

The basic components of GGBS comprise generally CaO (30%-48%), MgO (28%-45%), Al_2O_3 (5%-18%) and SiO_2 (1%-18%), which are in principle the same as that of Portland cement (Wang & Reed, 1995). Other minor components including Fe_2O_3, MnO, TiO_2 and SO_3 are also present in GGBS. The compositions do not change very much so long as the sources of iron ore, coke and flux are consistent (Bye, 1999).

2.4.2 Alkalis

Alkali metal ions are present in granulated blastfurnace slag as an integral part of the glass structure. Consequently, the water-soluble alkali content is low (Concrete Society, 1991).

2.4.3 Sulphides

There is generally a small amount of calcium sulphide in GGBS. The BS EN limits the total sulphide content of GGBS to 2.0% (BS EN 15167-1:2006), as compared to a limit of 3.0% in GB/T 203-2008 (GB/T 203-2008). The presence of such a small amount of sulphide can cause a colour change of the fresh concrete.

2.4.4 Chloride

Both the UK and Mainland China standards specify an upper limit of 0.1% on the chloride content (BS EN 15167-1:2006 and GB/T18046-2008).

2.4.5 Chemical Reaction of GGBS

BS 6699 adopts the chemical modulus (i.e. the amount of CaO, MgO or $A1_20_3$ in GGBS) to describe the reactivity of GGBS. In general, the rate of reactivity of GGBS increases with increasing amount of CaO, MgO or $A1_20_3$, but decreases with increasing amount of SiO_2. BS 6699 requires that (CaO + MgO + $A1_20_3$)/SiO_2 should be greater than 1.0. In addition, the rate of reactivity of GGBS also increases as the CaO/SiO_2 ratio increases. BS 6699 limits the CaO/SiO_2 ratio to a maximum value of 1.4, although a value of 1.5 would give optimum reactivity (Concrete Society, 1991).

BS EN 15167-1 adopts a system called activity index for assessing the reactivity of GGBS. The activity index is the ratio (in percent) of the compressive strength of a mortar cube made with 50% GGBS and 50% Portland cement to that of a mortar cube with 100% Portland cement. The BS EN requires the minimum activity index at 7 days and 28 days to be 45% and 70% respectively as compared to the GB/T18046 requirements of 55% and 75%

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for grade S75 GGBS (BS EN 15167-1:2006 and GB/T18046-2008). For grade S105 GGBS, GB/T18046's requirements on the minimum activity index at 7 days and 28 days are 95% and 105% respectively. It seems that the minimum activity requirements of GB is higher than those of BS EN.

Atwell (1974) reported that GGBS did not set on its own with water if the fineness was around 3000-3500 cm^2/g. Its reactivity was activated by the lime liberated by the hydration process when mixed with Portland cement.

Richardson (2006) reported that in the early hydration of GGBS and Portland cement, the Portland cement released alkali metal ions and calcium hydroxides (CH). The slag reacted initially with calcium hydroxide resulting in the breaking down of the glassy structure of the slag. As hydration continues, more calcium hydroxides would precipitate from the Portland cement and calcium silicate hydrate (CSH) would be produced. As CSH are developed, they would fill the pores and contribute to strength development and chemical resistance. The additional CSH fills the pores making pore size refined.

2.5 Other Properties

2.5.1 Setting Time

GGBS concrete requires longer setting times than Portland cement concrete, probably due to the smooth and glassy particle forms of GGBS. The setting time also increases with increasing percentage of GGBS replacements. Duos and Eggers (1999) reported that if the temperature was at 23°C, the setting times were not significantly affected by the GGBS replacement levels. Other research reported that if the GGBS replacement level was less than 30%, the setting times would not be significantly affected (Slag Cement Association, 2005).

The setting times of GGBS concrete are sensitive to low ambient temperatures. For example, in a development project in Beijing, the de-moulding time was delayed by six to eight hours when the ambient temperature was lowered from 15°C to below 5°C (北京市高強混凝土有限責任公司, 2004).

2.5.2 Bleeding

A reviewing of literature reveals that there have been contradictory views on the bleeding of GGBS concrete. It has been reported by the Concrete Society (1991) that when GGBS replacement level is less than 40%, bleeding is generally unaffected. At higher replacement levels, bleeding rates may be higher (Concrete Society, 1991).

Slag Cement Association (2005) reported that most of the concrete made with GGBS in the USA had less bleeding than concrete made with cement alone, because the slag was grounded to a finer state than normal cement. On the other hand, coarser slag had equal or greater bleeding (Slag Cement Association, 2005).

In general, bleeding reduces with increase in the fineness of cementitious material used. GB/T18046 requires the minimum fineness of GGBS to be 3000 cm^2/g for grade S75 GGBS,

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4000 cm^2/g for grade S95, and 5000 cm^2/g for grade S105 respectively (GB/T18046-2008). Concrete with GGBS of grade S95 or grade S105 may have less bleeding than that of Portland cement (with fineness at around 3500 cm^2/g), whereas the bleeding in concrete with GGBS of grade S75 may be greater.

2.5.3 Workability

It is generally known that GGBS particles are less water absorptive than Portland cement particles and thus GGBS concrete is more workable than Portland cement concrete. For equivalent workability, a reduction in water content of up to 10% is possible (Richardson 2006). Researchers believed that this was due to the smooth and dense surface of the slag that made GGBS less water absorptive as compared to Portland cement (ACI Committee 233R, 1995). Some researchers reported that GGBS concrete mixes exhibited 20% to 50% greater slumps than ordinary concrete with the same water/cementitious content ratio (Duos & Eggers, 1999).

2.5.4 Creep

It has been reported that under practical conditions, the creep of GGBS concrete was similar to that of Portland cement (Concrete Society, 1991). Other researchers reported that GGBS concrete had similar or lower creep with replacement levels ranging from 30% to 70% (Brooks et al, 1992).

2.5.5 Drying Shrinkage

Most of the papers in the literature reported that the use of GGBS has little influence on the drying shrinkage of concrete. Some reported that GGBS would lower the drying shrinkage potential under certain conditions. It has been reported that under a curing condition of 20^{o}C and 60% relative humidity after a period of 28 days storage in water, the drying shrinkage of 50% GGBS concrete was about 10% lower than the OPC concrete (Concrete Society, 1991). Li & Yao (2001) reported that the use of ultra fine GGBS and silica fume could greatly reduce the drying shrinkage.

2.5.6 Hydration Temperature

Experiments showed that the inclusion of GGBS in concrete could significantly reduce the temperature rise during the hydration of cement (Bamforth, 1980). Researchers found that, with 70% GGBS replacement, it was possible to reduce the hydration temperature by about 30% (Tongji University, 2004).

Other researchers also found that the temperature rise was reduced when GGBS replacement level was increased up to 70%. The reduction was significant only at the 70% replacement level (Tam et al, 1983).

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2.5.7 Elastic Modulus

It is widely accepted that the effect of GGBS replacement on the elastic modulus of concrete is negligible (Concrete Society, 1991).

2.6 Influences on Durability

It is generally known that the inclusion of GGBS in concrete can improve the durability. GGBS concrete generally has a low permeability resulting in reduced chloride penetration, enhanced resistance to sulphate attack and alkali silica reaction as compared with ordinary Portland cement concrete (Hollinshead et al, 1996). Research findings indicate that the rate of corrosion of steel in cracked GGBS concrete at cover depths of 20 mm and 40 mm would be significantly reduced by at least 40% when compared to that of Portland cement concrete (Scott & Alexander, 2007).

It has been reported that a higher calcium hydrate (CH) content will in general produce concrete of poor durability due to an inhomogeneous mix with poor bonding between calcium silicate hydrate (CSH) and CH. Higher CH contents will lead to a greater permeability and a lower durability. The GGBS particles are retained in CSH form resulting in a hardened paste of greater density and smaller pore size as compared to Portland cement paste. Smaller pore size gives rise to a lower permeability and hence a higher durability in general (Feldman, 1983; ACI Committee 233R, 1995).

2.6.1 Chloride Ingress

GGBS concrete has generally lower permeability and hence better resistance to chloride penetration. It has been reported that the pore structure of the concrete was changed during the reaction of GGBS particles with the calcium hydroxide and alkalis released during hydration. The pores were filled with calcium silicate hydrates instead of calcium hydroxide. Researchers reported that as the GGBS content increased from zero to 50%, the chloride permeability dropped significantly at 90 days (Richardson, 2006). Ryou & Ann (2008) also reported that the rate of chloride transport was reduced to the lowest level in concrete with 60% GGBS replacement.

2.6.2 Sulphate Resistance

Cement with 65% GGBS by mass is specified as high sulphate resistance cement according to DIN 1164 (Geiseler et al, 1995). However, some studies find that GGBS of high alumina content and high fineness level may affect the sulphate resistance of GGBS concrete (Lee et al, 2006).

2.6.3 Carbonation

Researchers from Tsinghua University reported that the amount of GGBS replacement was not an important factor with regard to the rate of carbonation of GGBS concrete

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(Tsinghua University, 2004). When the water/(GGBS+OPC) ratio is 0.5, GGBS concrete showed an increased carbonation depth (about 3-4 mm during the construction period) as compared to Portland cement concrete of the same grade. However, such small increase in the carbonation depth had no practical implication and it would not increase the risk of corrosion of the reinforcement in GGBS concrete. Laboratory studies on accelerated carbonation test by Tsinghua University found that when the water/(GGBS+OPC) ratio is reduced from 0.5 to 0.4, the 28-day carbonation depth is reduced from over 10 mm to about 4-6 mm.

2.6.4 Alkali Aggregate Reaction

Many researchers confirmed that GGBS had the ability to reduce the deleterious expansion caused by alkali aggregate reaction (AAR), especially when GGBS was used to replace Portland cement of high alkali content. GGBS has been used in the UK, Germany, and Japan as a means to reduce the risk of damage due to AAR. In the UK, high levels of GGBS (50%) are generally used (Concrete Society, 1991).

Wang & Read (1995) reported that the ability of GGBS to reduce the deleterious effect of AAR was due to its low reactive alkali content and its ability to inhibit AAR. The overall lime-to-silica (Ca/Si) ratio of the hydration products (CSH) was reduced by inclusion of GGBS in the concrete as partial replacement of Portland cement as compared to pure Portland cement concrete. The hydration products of low Ca/Si ratio can 'immobilize' free-alkalis and hence reduce the risk of AAR (Wang & Read, 1995).

2.7 Strength Development

2.7.1 Early Age Strength Development

General literature review indicates that GGBS concrete has lower early strengths because the rate of initial reaction of GGBS is slower than that of Portland cement. GGBS is therefore generally grounded to a finer state than Portland cement. Researcher reported that, as the fineness of GGBS increased from around 4000 cm^2/g to 6000 cm^2/g, the 28-day strength increased significantly (Hamling, 1992).

Lane & Ozyildirum (1999) reported that the early strengths (up to 28 days) of concrete mixes (with 25%, 35%, 50%, and 60% GGBS replacements) were lower than that of Portland cement concrete mixes. By 56 days, the strength of 50% and 60% GGBS mixes exceeded that of the Portland cement mix, and by one year all GGBS mixes were stronger than the Portland cement mixes (Lane & Ozyildirum, 1999).

2.7.2 Influence of Curing Temperature and Duration

Curing temperature has an important effect on the curing duration required to achieve the designed strength or durability. The curing temperature affects the rate of hydration of cement, which affects the strength development of concrete (Meeks & Nicholas, 1999). Neville (1981) reported that the rate of hydration increased with a rise in the curing temperature. This is beneficial to the early strength development of concrete up to the age of

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seven days. When the curing temperature is about 30°C or above, the strength of seven days onwards may be adversely affected. Neville (op cit) explained that a high initial temperature might cause the initial hydration rate to be too high such that there would be insufficient time available for the hydration products to diffuse away from the cementitious grain and precipitate uniformly in the interstitial space. As a result, a high concentration of the hydration products was built up around the hydrating grains retarding the subsequent hydration process and adversely affected the long-term strength of concrete (Neville, 1981).

Concrete containing GGBS has slower reaction rates. A longer curing duration is essential for proper development of the properties of GGBS (Neville, 1996). Some researchers (Meeks & Nicholas, 1999) recommend a minimum curing period of three days for high performance or durable GGBS concrete. The reason is that durability is controlled mainly by the quality of the concrete at surface and good curing is important for the quality of concrete at surface.

High GGBS replacement concrete is more susceptible to poor curing conditions than Portland cement concretes probably due to the reduced formation of hydrate at early ages. Researchers found that curing in air lowered the strength by 21% and 47% for 50% and 65% GGBS replacement concrete respectively as compared to moist-cured samples at 180 days (Richardson, 2006). The strength for a 50% GGBS replacement mix with an initial seven days moist curing followed by air curing is not significantly affected as compared to the moist-cured sample of the same GGBS replacement level.

2.8 Typical Level of Replacement

In the USA, the levels of GGBS replacements range from 25% to 50% for high strength concrete (Slag Cement Association, 2005). In another study, it was found that slag replacement level of 40 to 60 % appeared to be the optimum level for high strength development (Richardson, 2006). In Canada, the replacement level is about 50% for control of alkali-silica reaction. For concrete to resist sulphate attack and achieve a lower early age heat generation, the level of replacement will need to be within 60% to 85% for mass concrete construction (Hooton, 2000). In China, the GGBS replacement level usually ranges from 30% to 40% for optimum strength performance (北京市高強混凝土有限責任公司, 2004). In Hong Kong, the Tsing Ma Bridge adopted a replacement level of about 65% in order to meet the stringent durability requirements.

3. DESCRIPTION OF TEST MATERIALS

The physical and chemical properties of the cement, GGBS and silica fume, and the physical properties of the aggregates used in the present investigation by PWCL are given in the interim report (Leung et al, 2009). These are reproduced in Tables 1 to 4 for easy reference.

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4. LABORATORY INVESTIGATION

4.1 Concrete Mix Design

The concrete mixes for the present study comprised a Portland cement concrete and four GGBS concrete mixes with a GGBS content of 30%, 50%, 70% and 80% respectively. The 50% and 70% mixes were repeated with the inclusion of 5% silica fume (SF) to investigate their enhancement effect on concrete durability. Grades 35 and 45 concretes were aimed for in the design, as these were the most commonly used concrete grades in Hong Kong. All the mixes have a target slump of between 100 mm and 200 mm. The K. Wah Concrete Company Limited carried out the trial mixes using two types of GGBS and derived the mix design. They also supplied the concrete for this study. The actual slump achieved varied between 105 mm and 145 mm. The details of the concrete mix design are given in Tables 5 and 6.

A total of 30 concrete mixes were produced. For each of concrete mixes, 138 concrete cubes were cast for strength tests and a concrete panel of 1 m^3 was cast to investigate the peak temperature and durability of the mix. All the concrete cubes were de-moulded within 24 hours of casting.

4.2 Test Procedures

The concrete was transported from a batching plant at Tai Po to a casting yard at Tsuen Wan by ready mix trucks. For each truckload of concrete, slump test was carried out in accordance with CS1:1990. In addition, the bleeding of concrete was measured in accordance with ASTM C232-99.

The cubes cast were stored in a range of curing environments and durations. The density and compressive strength of the cubes were determined in accordance with the procedures laid down in CS1:1990. A concrete block of 1 m^3 was also cast for each mix. The block was insulated with 200 mm thick polystyrene. Thermocouples were installed at the center of the panels to measure the temperature rise. Cores were taken from the panel for the Rapid Chloride Penetration Test in accordance with ASTM C1202-91.

4.3 Curing Environment

After the cubes were cast, they were stored for 24 hours on site before de-moulding. The cubes were then cured under various environments as summarised in Table 7. A total of seven curing environments were investigated in the study. The environments were chosen to simulate as far as possible a range of in situ curing conditions that may be encountered on site. For example, curing environments E2 to E4 were intended to simulate possible conditions where curing was insufficient. E5 was intended to simulate concreting in cold weather, whereas E6 and E7 simulated the conditions in mass concrete pours. Curing environment E1 is the standard (27°C) water curing as specified in CS1 for compliance testing in Hong Kong.

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4.4 Age of Testing

For each mix, sets of three cubes were cast and cured under each of the curing environments and these were then tested at each of the following test ages: 3 days, 7 days, 28 days, 56 days, 91 days, 182 days and 364 days. A total of 4140 cubes were cast.

Sets of three core samples were prepared and subjected to Rapid Chloride Penetration Test (RCPT) (ASTM C1202-91) at each of the following test ages: 28 days, 56 days and 91 days, to provide an indication of the concrete's ability to resist chloride ion penetration. A total of 270 core samples were tested.

4.5 Test Results

The compressive strength and mean strength results for all the mixes are given in Tables 8 to 37.

5. DIAGNOSIS OF TEST RESULTS

5.1 Bleeding of GGBS Concrete

Bleeding of GGBS concrete has been one of the common concerns of engineers, especially for mixes where the setting times were retarded. The bleeding of GGBS concrete is related to the fineness of the GGBS. Concrete made with GGBS of high fineness would have lower bleeding. In this study, the average fineness of GGBS used was around 4520 cm^2/g. This is finer than that of cement (viz. 3430 cm^2/g). From the results in Tables 5 and 6, the average bleeding rate of the GGBS concrete was about 0.4 as compared to 0.6 for Portland cement concrete. There was slightly less bleeding in GGBS concrete as compared to Portland cement concrete. When silica fume were added to the GGBS concrete, the bleeding rates were generally much improved. This may be due to the fact that silica fume is much finer than that of cement and GGBS.

5.2 Peak Temperature of Large Pour

The peak temperature and corresponding ambient temperature for each mix are summarized in Table 42. Typical temperature profiles for Grade 30 and Grade 45 GGBS concrete are shown in Figure 2, which indicate that the peak temperature generally occurred around 48 hours after casting.

It is generally believed that the inclusion of GGBS can reduce the hydration temperature of large concrete pours. Literature review suggests that it is possible to achieve a 30% reduction in hydration temperature by replacing 70% of the cement by GGBS. The results from the testing by the PWCL, however, indicate otherwise. In the present study, the peak temperatures of GGBS concrete mixes were in general higher than that of Portland cement concrete. As the mixes were not designed with the intention to lower the peak temperatures but with the intention to achieve the same 28-day target strengths, it is noted that the GGBS mixes generally had higher total cementitious contents than the Portland cement concrete mixes. The increase in total cementitious content would have led to an increase in

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the peak temperature of the mixes.

One way to analyse the results is to normalise the concrete temperature rise to that caused by 100 kg of total cementitious materials. The normalised results are shown in Table 42. It can be seen that for both the Grade 35 and Grade 45 concrete, the peak temperatures occurred at 50% GGBS replacement, being up to 16% higher than that of OPC concrete. The peak concrete temperatures reduced as the GGBS replacement level was further increased. At 80% GGBS replacement level, the normalised peak temperatures were on average about 14% lower than that of OPC concrete. The effect of reduction in hydration temperature of GGBS concrete is noticeable only at a GGBS replacement level of 80%.

The PWCL's results also showed that the inclusion of silica fume would appear to cause a reduction in the normalised peak temperature. At 75% GGBS replacement, a 5% dosage of silica fume would lower the normalised peak temperature by as much as 30%.

Should a lower heat of hydration be required, the total cementitious content as well as the water content could be lowered while maintaining the W/C ratio. The workability could be achieved by the addition of superplasticiser. The casting temperature would also need to be controlled in order to lower the peak temperature.

It is also noted that the GGBS used in this experiment had a specific surface close to 4500 cm^2/g. This would be classified as Class S95 in the Chinese Standard. Perhaps Class S75 slag (Fineness of approximately 3500 cm^2/g) would be a better choice to lower the heat of hydration.

The PWCL's result highlighted the importance of temperature control even for GGBS mixes. This perhaps can be another interesting topic for future research.

5.3 Consistency of Test Results

From the compressive strength results given in Tables 8 to 37, it can be seen that for the same mix, the compressive strengths of cubes subjected to the same curing environment and tested at the same age are generally consistent. Therefore, batch variation is small.

An analysis of the standard deviation (SD) of all the sets of three cubes for all the mixes has been carried out. It is found that for Grade 35 mixes, the mean SD of all the sets is 1.1 MPa and 97.7% of all the sets of results were within a SD of 3.0 MPa. For Grade 45 mixes, the mean SD of all the sets is 1.3 MPa and 96.2% of all the sets of results were within a SD of 3.0 MPa. Therefore, the overall mix variation is small.

The small batch variation justifies the use of the arithmetic average strength of the set of three cubes as the statistical mean compressive strength. Summaries of the mean compressive strengths for all the mixes are given in Tables 38 to 41.

5.4 Basis of Analysis of Results on Compressive Strength

As the 28-day strengths of cubes under standard curing condition deviate slightly from

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their target strength, it would be difficult to compare the strength development of various mixes based on actual results. In order to facilitate comparison of the rate of strength development of the various mixes under different curing environments, the mean compressive strengths for each mix at various ages have been converted to relative strength percentages by comparing them with the 28-day mean compressive strength under the standard curing condition E1.

Relative strength percentage is defined as follows:

$$\text{Relative strength percentage (RSP)} = \frac{\text{Mean compressive strength}}{\text{28 - day mean compressive strength under standard curing (i.e. E1)}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots(1)$$

The above effectively converts the RSP of standard cured cubes to 100% at 28 days for all the mixes. The results of the relative strength percentage for the 30 mixes are given in Tables 43 to 46.

5.5 Strength Development of GGBS Concrete

5.5.1 Early Age Strength Development under Normal Curing

The early age strength characteristics of a concrete cube can be observed from its 3-day and 7-day strengths. Literature review indicates that GGBS concrete in general have lower early age strength (3 days and 7 days) as compared to Portland cement concrete.

The results from the PWCL are given in Tables 43 to 46. The relative strength percentages of GGBS concrete cured under standard curing environment (i.e. water curing at 27^{o}C) were all below that of the control mixes M1 and M2. At 3 days, the RSP of GGBS mixes varied from 34% to 46% as compared to that of the control mixes of around 60%. At 7 days, the RSP for GGBS concrete varied from 56% to 71% as compared to around 74% to 81% for the control mixes. The typical early age strength developments for Grade 35 concrete are shown in Figures 3.

The rate of gain in strength for the GGBS mixes between 7 days and 28 days was however higher than that of the control mixes, so that at 28 days both mixes achieved the target strength.

The PWCL results are generally in agreement with the findings of the literature review.

5.5.2 Long Term Strength Development under Normal Curing

The results from this study are consistent with the common observation that GGBS concrete has an enhancing effect on the long-term strength development of concrete.

Under standard curing environment E1 (27^{o}C water curing for 28 days, followed by air curing until testing), the cube results given in Tables 43 to 46 indicated that the GGBS concrete generally gained further strengths from 28 days to 364 days, representing a post

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28-day strength gain of about 12% to 29%.

The results from the PWCL also established that there were cases of strength regression in some of the GGBS concrete mixes, in particular the mixes with 30% GGBS replacement. The cubes gained maximum strength between 90 and 182 days and then the strength reduced slightly with time. At 364 days, there was a strength reduction of about 10% from its peak strength. The exact reason for this observation is unknown, as it was neither observed in mixes at higher GGBS dosage, nor in the mixes with silica fume.

5.5.3 Influence of Silica Fume on Strength Development under Normal Curing

The results in Tables 43 to 46 indicate that the influence of silica fume on the strength development of GGBS concrete is insignificant. The RSP for the early ages of 3-day and 7-day were generally similar to that of GGBS concrete and were about 15% to 20% lower than that of Portland cement concrete. The 28-day strength of cubes under standard curing had relatively higher strength values than the Portland cement concrete.

It is noteworthy that no strength regressions were observed in the mixes containing silica fume.

5.5.4 Effect of Curing Temperature on Strength Development

The influence of curing temperature on the strength development of various concrete mixes is illustrated by comparing the relative strength percentages of the mixes under curing conditions E1, E5, E6 and E7. The results for the Grade 35 and Grade 45 mixes are shown in Figures 4 and 5 respectively.

Literature review indicates that a high initial curing temperature has a beneficial effect on the early strength (3 or 7 days) of concrete in general. The results from this study are in general agreement with the results reported in the literature review. It appears that low temperature curing has an insignificant influence on Portland cement concrete but would significantly affect the early strength development of GGBS concrete.

The results from the PWCL revealed that GGBS mixes suffered a 20% reduction in strength under low temperature curing condition E5 (i.e. at 10°C in water for 3 days followed by 20°C in water for 24 days then air curing) as compared to that under standard curing condition E1 (i.e. at 27°C). The strength development recovered with time with nearly all the mixes reaching their target strengths at 56 days.

Literature review also shows that high temperature curing has detrimental effects on the long-term strength development. The results from this study confirmed that under high temperature curing of 75°C, the long-term strength development of all the concrete mixes was significantly affected. The 28-day relative strength percentage fell to between 71% and 94%. Some of the mixes cannot achieve their target strengths even after one year.

The peak temperatures obtained from the concrete panels cast in this study were between 72°C and 94°C. The temperature could therefore be significantly higher than that

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used in curing condition E7 (i.e. at 75^{o}C). In practice, high temperature curing conditions are often encountered in Hong Kong, especially in mass pours and in foundations in the summer. The results indicate that the strength of Portland cement and GGBS concrete in a mass pour cast in the hot summer period may not all reach their target strengths even after one year.

5.5.5 Effect of Curing Duration on Strength Development

It is generally believed that the strength development of concrete is sensitive to the period of curing. The results from PWCL confirmed the importance of ensuring sufficient curing as shown in Figure 6 for the grade 35 concrete using SG slag.

As can be seen from the Figure 6, none of the cubes subjected to air curing only (i.e. curing environment E4) achieved their 28-day target strengths. The GGBS mixes only achieved an average of 67% of their target strengths as compared to 79% with the Portland cement mixes. Even at the age of one year, none of the cubes achieved their 28-day target strengths.

For cubes that had been cured for three days (i.e. curing environment E3), the average 28-day strength of GGBS concrete cubes is 87% of their target strengths. In comparison, the Portland cement cubes achieved 99% of their target strengths. After one year, all the cubes achieved strengths above their 28-day target strength.

For cubes that had been cured for seven days (i.e. curing environment E2), all the GGBS concrete cubes achieved between 90% and 99% of their target strengths at 28 days as compared to 103% to 109% for Portland cement cubes.

The PWCL's results showed that GGBS concrete mixes need a longer curing period than the Portland cement concrete for strength development.

5.6 Durability of GGBS Concrete

5.6.1 Effect of GGBS Content on Durability

The results of RCPT from the 30 concrete mixes at 28 days, 56 days and 91 days are summarised in Table 47. For mixes without silica fume, the RCPT results were plotted against the GGBS percentage in Figure 7. From the PWCL's results, it is clear that the control Portland cement mixes were very permeable and did not have much resistance to chloride penetration. The inclusion of GGBS has improved the resistance to chloride penetration.

According to ASTM, the chloride penetrability of a concrete is classified as high, if the amount of charge passed in a rapid chloride penetration test is greater than 4000 Coulombs. The 91-day RCPT results indicate that for nearly all the mixes with GGBS content not exceeding 50%, their chloride permeability could be classified as high. With the GGBS content increased to 70%, the chloride permeability could be classified as low. For mixes with 80% GGBS replacement, the chloride permeability would be classified as very low. The results indicate that the GGBS content should be at least 70% in order to significantly improve the durability of concrete.

The PWCL's results also confirmed that as the concrete matures, its resistance to chloride penetration also improves, albeit by a relatively small margin.

5.6.2 Effect of Silica Fume on Durability

It is generally believed that the inclusion of silica fume (SF) would significant improved the concrete durability. That is why the marine concrete specification (Standing Committee on Concrete Technology, 2000) requires that a SF dosage of 5% to 10% of the total cementitious content should be used. This general understanding is clearly demonstrated by the PWCL's results as shown in Figure 8. It can be seen that there was a substantial reduction in RCPT values after the addition of SF, as shown by comparing the RCPT values in Figure 7 and Figure 8.

All the mixes with SF achieved a RCPT value of less than 1000 coulombs, which indicate that their permeability would be classified as low. The RCPT values would be further reduced with increased dosage of GGBS, which tallies with the findings of tests on concrete mixes without SF. The results indicate that both SF and GGBS would improve the durability of concrete, but the effect of SF is comparatively far more significant.

It is however reported (Poon et al, 2001) that, under high temperature, concrete with a SF dosage more than 5% replacement will have a high risk of explosive spalling.

5.6.3 Effect of Concrete Maturity on Durability

The results in Table 47 indicate that as the concrete matures, its ability to resist chloride penetration also improves. The effect is more prominent for permeable mixes but the degree of improvement is relatively small when compared with that resulting from the addition of silica fume or a higher GGBS replacement.

5.7 Effect of Source of GGBS on Performance

In the PWCL's study, two different sources of slag were used, namely slags from Dong Run Pai (CRC) (東潤牌) and Guangdong Shao Gang (SG) (廣東韶鋼). An attempt to study the influence of the two slags on strength development was carried out by comparing the relative strength percentage of the same mixes from Tables 43 to 46. The results are shown in Tables 48 and 49 respectively. A mean difference is also given in the two tables. For grade 45 concrete under standard curing condition E1, the maximum difference in the mean strength percentage is 7% in favour of the CRC slag. This is reduced to 1% at 52 weeks.

Although the CRC slag seems to give slightly higher strength than the SG slag in some of the mixes but this trend is not consistent. As a lot of factors can influence concrete strength, no definite conclusion can be drawn from the results in this aspect.

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6. CONCLUSIONS

The PWCL has carried out a laboratory investigation on the strength development of GGBS concrete. A total of 30 concrete mixes and seven curing environments were included in the study. Based on the results up to a test age of 364 days, the following conclusions can be drawn:

(a) The PWCL's findings indicate that bleeding of concrete is not affected significantly by the inclusion of GGBS. When used in conjunction of silica fume, there appears to be a noticeable improvement in respect of the degree of bleeding.

(b) As the temperature control measures were not imposed for the mixes used, there was no significant reduction in the peak temperature of GGBS concrete unless the replacement percentage is at least 80%. Temperature control may need to be imposed to limit the peak temperature of the GGBS concrete.

(c) The inclusion of GGBS appears to have a slight retarding effect on the early strengths of concrete. The 7-day strengths of GGBS concrete were between 56% and 71% of the 28-day strengths, as compared to about 80% for Portland cement concrete.

(d) The strength development of GGBS concrete was affected by the curing temperature. Low curing temperature would result in low early strength of GGBS concrete. For high temperature curing at 75°C, the 28-day strengths all fell short of their design strength and there may be a need to limit the peak temperature of concrete in mass pours in practice.

(e) The GGBS concrete would require a longer curing period than that of Portland cement concrete. Insufficient curing (less than 3 days) could severely hamper the strength development.

(f) The inclusion of GGBS would improve the concrete's ability to resist chloride penetration but the GGBS replacement percentage will need to be at least 70% for this purpose.

(g) The inclusion of silica fume would significantly improve the concrete durability.

(h) Literature review indicates that GGBS replacement levels of between 30% and 40% were often adopted to give the optimal strength performance. For resistance to sulphate

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attack and lower early age heat generation, the replacement levels used were often from 60% to 85% for mass concrete construction.

(i) The source of GGBS does not appear to have a significant effect on the performance of GGBS concrete so long as the GGBS complies with the relevant standards.

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Table 1 - Physical and Chemical Properties of Cement

Test	BS EN197-1:2000 Strength Class 52.5N Specification	Unit	Results
Physical Properties			
Density	Not Specified	kg/m^3	3170
Fineness (specific surface)	Not Specified	cm^2/g	3430
Standard consistence	Not Specified	(%)	27
Initial setting time	> 45 min	(min)	215
Final setting time	Not Specified	(min)	270
Soundness (expansion)	≤ 10	(mm)	0.5
Flexural strength (mean 2 days)	Not Specified	MPa	5.3
Flexural strength (mean 28 days)	Not Specified	MPa	10.1
Compressive strength (mean 2 days)	Min. 20 N/mm^2	MPa	23.6
Compressive strength (mean 28 days)	Min. 52.5 N/mm^2 Max. 72.5 N/mm^2	MPa	65.2
Chemical Properties			
K_2O	Not Specified	%	0.44
Na_2O	Not Specified	%	0.25
SO_3	Max. 4.0%	%	2.2
Insoluble residue	Max. 5.0%	%	0.2
Loss-on-ignition	Max. 5.0%	%	1.9
Chlorine content	Max. 0.10%	%	0.01
Total alkali (equivalent Na_2O)	Not Specified	%	0.54

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Table 2 - Physical and Chemical Properties of GGBS

Test	Unit	BS 6699:1992 Requirement	GGBS - CRC	GGBS - SG
Physical Properties				
Density	kg/m^3	Not specified	2880	2910
Fineness (specific surface)	cm^2/g	Not less than 2750	4490	4550
Standard consistence	%	Not specified	29	27.5
Initial setting time	min	#	220	235
Soundness (expansion)	mm	Not specified	0	0.5
Flexural strength (mean 7 days)	MPa	≤ 10	7.5	6
Flexural strength (mean 28 days)	MPa	Not specified	9.1	9.4
Compressive strength (mean 7 days)	MPa	≥ 12	29.6	26
Compressive strength (mean 28 days)	MPa	≥ 32.5	47.4	47.1
Chemical Properties				
Loss-on-ignition	%	< 3.0%	1.1	0.6
Sulphate content (SO_3)	%	< 2.5%	0.2	0.1
Residue insoluble in hydrochloric acid and sodium carbonate	%	< 1.5%	0.7	0.3
Manganese content Manganese oxide content (MnO) Manganese oxide content (Mn_2O_3)	% % %	< 2.0%	0.5 0.6 0.7	0.7 0.9 1.0
Chloride ion content	%	< 0.1%	0.02	0.01
Magnesia content (MgO)	%	< 14%	10.3	9.4
Pure Silica content (SiO_2)	%	Not specified	32.6	31.8
Calcium oxide content (CaO)	%	Not specified	36.0	37.6
Chemical moduli i) (CaO+MgO)/(SiO_2) ii) (CaO)/(SiO_2)	%	> 1.0 < 1.4	1.4 1.1	1.5 1.2
Sodium oxide content (Na_2O)	%	Not specified	0.4	0.3
Potassium oxide content (K_2O)	%	Not specified	0.6	0.5
Alkali content	%	Not specified	0.7	0.6
Iron oxide content (Fe_2O_3)	%	Not specified	0.5	0.4
Alumina content (Al_2O_3)	%	Not specified	14.8	14.5
Sulphur content	%	< 2.0%	0.9	0.3
Moisture content	%	< 1.0%	0.1	< 0.1

Legend:
\# The initial setting time of the combination of GGBS and PC shall be not less than the setting time of the PC when tested on its own. (Initial setting time of PC = 175 min.)

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Table 3 - Physical Properties of Aggregates

Test	Unit	GS 2006 Specification	Coarse Aggregates		Fine Aggregates
			20 mm	10 mm	
1. Particle size distribution					
(Percentage passing)					
Size of BS Sieve (mm)					
37.5	%		100		
20	%		95		
14	%		43	100	
10	%		9	98	100
5	%		2	14	96
2.36	%			5	77
1.18	%				58
0.6	%				42
0.3	%				29
0.15	%				18
2. Flakiness index	-	< 30%	9	20	
3. Elongation index	-	< 35%	26	22	
4. Ten per cent fines value	kN	> 100 kN	150		
5. Water absorption	%	< 0.8%	0.7	1.0	0.7
6. Clay, silt & dust content	%	Not specified	0.5	1.5	10
7. Relative density	-				
(on oven-dried basis)		Not specified	2.58	2.57	2.59
(on saturated and surface-dried basis)		Not specified	2.60	2.59	2.61
(apparent)		Not specified	2.63	2.64	2.64

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Table 4 - Physical and Chemical Properties of Silica Fume

Test	Unit	Specification	Results
Physical Properties			
Moisture Content (by mass of dry ash)	%	max 3	0.8
Fineness > 45 micron	%	max 10	1.4
Specific Gravity		-	2.18
Pozzolanic Activity at 7 days (MPa) -Control Sample -Test Sample		 - -	 30.7 27.3
Accelerated Pozzolanic Activity Index with OPC at 7 days minimum % of Control	%	min 85.0	130.4
Soundness Expansion	%	< 0.2	0.05
Chemical Properties			
SiO_2	%	min 85.0	93.7
SO_3	%	max 1.0	0.6
Loss on Ignition	%	max 6.0	3.5
Note: Tests are carried out in accordance with CAN/CSA-A23.5 - M86 (Canadian Standard).			

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Table 5 - Mix Proportions of Grade 35 Concrete

Grade 35

Mix No.	Proportion (GGBS/ PC/SF)%	Total Cementitious Content (kg)	Cement (kg)	GGBS (kg)	SF (kg)	20 mm Agg. (kg)	10 mm Agg. (kg)	Fine (kg)	Water (kg)	Total Admixture (kg)	W/C Ratio	Slump (mm)	Bleeding (%)
M1	0/100/0	390	390	0	0	625	250	815	210	1.48	0.54	115	0.6
M3/35C	30/70/0	415	291	124	0	620	265	790	218	1.96	0.53	125	0.1
M4/35C	50/50/0	370	185	185	0	625	250	845	200	1.98	0.54	140	0.2
M5/35C	70/30/0	390	117	273	0	650	250	805	204	2.04	0.52	135	0.4
M6/35C	80/20/0	480	96	384	0	695	270	655	200	2.2	0.42	115	0.6
M7/35C	47.5/47.5/5	400	190	190	20	655	245	745	212	1.76	0.53	110	0.2
M8/35C	67.5/27.5/5	400	110	270	20	655	250	750	200	1.95	0.50	105	0.1
M9/35C	75/20/5	435	87	326	22	660	245	720	201	2.39	0.46	105	0.2
M3/35S	30/70/0	415	291	124	0	620	265	790	218	1.66	0.53	115	0.6
M4/35S	50/50/0	370	185	185	0	625	250	845	200	1.81	0.54	130	0.7
M5/35S	70/30/0	390	117	273	0	650	250	805	204	1.87	0.52	135	0.6
M6/35S	80/20/0	480	96	384	0	695	270	655	200	2.17	0.42	135	0.4
M7/35S	47.5/47.5/5	400	190	190	20	655	245	745	212	1.68	0.53	110	0.5
M8/35S	67.5/27.5/5	400	110	270	20	655	250	750	200	2.43	0.50	120	0
M9/35S	75/20/5	435	87	326	22	660	245	720	201	2.39	0.46	115	0.1

Table 6 - Mix Proportions of Grade 45 Concrete

Grade 45

Mix No.	Proportion (GGBS/ PC/SF)%	Total Cementitious Content (kg)	Cement (kg)	GGBS (kg)	SF (kg)	20 mm Agg. (kg)	10 mm Agg. (kg)	Fine (kg)	Water (kg)	Total Admixture (kg)	W/C Ratio	Slump (mm)	Bleeding (%)
M2	0/100/0	445	445	0	0	640	265	745	208	1.69	0.47	125	0.5
M10/45C	30/70/0	475	333	142	0	660	275	680	221	1.81	0.47	135	0.2
M11/45C	50/50/0	450	225	225	0	655	270	720	204	1.93	0.45	140	0.4
M12/45C	70/30/0	485	146	339	0	685	275	650	208	2.22	0.43	120	0
M13/45C	80/20/0	550	110	440	0	710	275	565	202	2.31	0.37	130	0.2
M14/45C	47.5/47.5/5	500	238	237	25	675	260	605	221	2.23	0.44	115	0
M15/45C	67.5/27.5/5	470.5	130	317	23.5	655	260	670	202	2.57	0.43	110	0
M16/45C	75/20/5	535	107	401	27	690	260	575	205	3.02	0.38	105	0
M10/45S	30/70/0	475	333	142	0	660	275	680	221	1.81	0.47	135	0.2
M11/45S	50/50/0	450	225	225	0	655	270	720	204	1.85	0.45	130	0.5
M12/45S	70/30/0	485	146	339	0	685	275	650	208	2.04	0.43	135	0.5
M13/45S	80/20/0	550	110	440	0	710	275	565	202	2.39	0.37	145	0.2
M14/45S	47.5/47.5/5	500	238	237	25	675	260	605	221	2.1	0.44	110	0.2
M15/45S	67.5/27.5/5	470.5	130	317	23.5	655	260	670	202	2.37	0.43	120	0.1
M16/45S	75/20/5	535	107	401	27	690	260	575	205	2.72	0.38	110	0

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Table 7 - Curing Environments of Concrete Cubes after Demoulding

Curing Environment	Description
E1	27^{o}C water curing for 27 days after demoulding and then air curing
E2	27^{o}C water curing for 7 day after demoulding and then air curing
E3	27^{o}C water curing for 3 day after demoulding and then air curing
E4	Air curing
E5	10^{o}C water curing for 3 days after demoulding and followed by 20^{o}C water curing for 24 days and then air curing
E6	50^{o}C water curing for 7 days after demoulding and followed by 27^{o}C water curing for 20 days and then air curing
E7	75^{o}C water curing for 7 days after demoulding and followed by 27^{o}C water curing for 20 days and then air curing
Notes: (1) The air cured cubes were stored in a room where the temperature was maintained at 20±5°C. (2) The mean relative humidity of the room over the test period was within 75%±10%.	

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Table 8 - Compressive Strength of Concrete Mix M1/35 under Various Curing Environments

Curing Environment	Age at Test								
	3 Days	7 Days	28 Days	56 Days	91 Days	182 Days		364 Days	
	Mean Strength (MPa)	Mean Strength (MPa)	Mean Strength (MPa)	Mean Strength (MPa)	Mean Strength (MPa)	Compressive Strength (MPa)	Mean Strength (MPa)	Compressive Strength (MPa)	Mean Strength (MPa)
E1	--	--	49.0	57.5	62.3	62.0 62.0 63.5	62.5	64.0 65.5 55.5	61.7
E2	--	36.2	50.3	51.7	55.7	55.5 56.5 57.0	56.3	55.5 55.0 52.5	54.3
E3	28.8	39.2	48.7	51.0	55.7	53.5 52.0 53.5	53.0	54.0 53.0 54.0	53.7
E4	27.3	32.8	38.5	38.7	43.8	41.0 42.5 42.0	41.8	42.5 44.5 42.5	43.2
E5	23.8	34.8	50.0	57.5	61.7	64.5 64.0 61.5	63.3	62.0 64.5 62.5	63.0
E6	31.8	42.7	49.8	52.8	55.7	60.0 60.5 60.5	60.3	62.0 62.0 61.0	61.7
E7	33.8	36.8	38.0	45.0	48.2	50.0 52.0 51.5	51.2	51.0 50.0 51.0	50.7
Note:	The details of the individual cube strengths of concrete mix between the ages of 3, 7 28, 56 and 91 days under the various curing environments are given in the interim report (Leung et al 2009).								

Table 9 - Compressive Strength of Concrete Mix M2/45 under Various Curing Environments

Curing Environment	Age at Test								
	3 Days	7 Days	28 Days	56 Days	91 Days	182 Days		364 Days	
	Mean Strength (MPa)	Mean Strength (MPa)	Mean Strength (MPa)	Mean Strength (MPa)	Mean Strength (MPa)	Compressive Strength (MPa)	Mean Strength (MPa)	Compressive Strength (MPa)	Mean Strength (MPa)
E1	--	--	58.7	69.5	72.2	73.0 74.0 75.5	74.2	72.5 73.5 71.5	72.5
E2	--	47.3	63.8	62.0	61.8	62.0 67.0 65.5	64.8	64.5 66.5 63.5	64.8
E3	36.0	47.8	59.5	61.7	62.5	60.0 64.0 60.5	61.5	61.5 54.5 62.0	59.3
E4	32.2	38.5	47.0	46.0	50.8	50.5 52.0 51.5	51.3	50.5 53.5 50.5	51.5
E5	28.5	44.3	60.0	68.8	68.3	72.0 74.0 73.5	73.2	72.0 75.0 74.0	73.7
E6	41.0	50.7	59.0	62.0	68.8	72.0 71.5 73.0	72.2	74.5 73.0 73.5	73.7
E7	42.5	44.5	47.7	52.2	57.7	57.0 59.5 58.5	58.3	59.0 59.0 56.5	58.2
Note:	The details of the individual cube strengths of concrete mix between the ages of 3, 7 28, 56 and 91 days under the various curing environments are given in the interim report (Leung et al 2009).								

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Table 10 - Compressive Strength of Concrete Mix M3/35C under Various Curing Environments

Curing Environment	Age at Test								
	3 Days	7 Days	28 Days	56 Days	91 Days	182 Days		364 Days	
	Mean Strength (MPa)	Mean Strength (MPa)	Mean Strength (MPa)	Mean Strength (MPa)	Mean Strength (MPa)	Compressive Strength (MPa)	Mean Strength (MPa)	Compressive Strength (MPa)	Mean Strength (MPa)
E1	--	--	56.3	62.5	65.5	64.5 65.0 67.5	65.7	63.5 61.5 64.0	63.0
E2	--	40.2	57.0	60.8	62.7	59.5 58.5 61.5	59.8	57.5 55.5 57.0	56.7
E3	26.2	39.3	52.7	56.3	56.0	56.5 57.0 57.0	56.8	51.0 47.5 56.5	51.7
E4	26.8	32.8	40.3	44.7	44.7	45.5 48.5 49.5	47.8	46.5 48.0 45.5	46.7
E5	20.5	33.2	55.0	63.3	66.2	68.0 67.5 67.5	67.7	64.0 60.0 61.0	61.7
E6	38.3	51.5	56.0	61.8	66.0	64.5 70.5 66.0	67.0	61.0 54.5 58.5	58.0
E7	37.3	41.2	43.0	51.8	53.3	56.5 56.5 56.5	56.5	46.0 45.5 48.5	46.7
Note:	The details of the individual cube strengths of concrete mix between the ages of 3, 7 28, 56 and 91 days under the various curing environments are given in the interim report (Leung et al 2009).								

Table 11 - Compressive Strength of Concrete Mix M4/35C under Various Curing Environments

Curing Environment	Age at Test								
	3 Days	7 Days	28 Days	56 Days	91 Days	182 Days		364 Days	
	Mean Strength (MPa)	Mean Strength (MPa)	Mean Strength (MPa)	Mean Strength (MPa)	Mean Strength (MPa)	Compressive Strength (MPa)	Mean Strength (MPa)	Compressive Strength (MPa)	Mean Strength (MPa)
E1	--	--	56.8	67.0	68.3	67.0 68.5 67.0	67.5	68.0 70.0 66.5	68.2
E2	--	35.0	53.5	58.3	57.2	60.5 61.0 63.0	61.5	62.5 61.5 60.0	61.3
E3	21.7	38.5	49.7	51.2	53.0	56.5 58.5 55.5	56.8	58.5 59.0 59.5	59.0
E4	22.3	29.3	38.3	40.7	42.8	47.5 49.5 44.5	47.2	49.5 48.0 48.5	48.7
E5	16.3	26.7	51.5	62.2	66.3	62.0 66.5 66.0	64.8	68.5 70.5 65.0	68.0
E6	40.7	54.8	57.2	65.0	68.8	66.5 67.5 66.0	66.7	68.0 71.0 68.5	69.2
E7	37.3	41.8	44.0	52.5	56.7	57.5 54.5 56.5	56.2	55.0 58.0 57.0	56.7
Note:	The details of the individual cube strengths of concrete mix between the ages of 3, 7 28, 56 and 91 days under the various curing environments are given in the interim report (Leung et al 2009).								

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Table 12 - Compressive Strength of Concrete Mix M5/35C under Various Curing Environments

Curing Environment	Age at Test								
	3 Days	7 Days	28 Days	56 Days	91 Days	182 Days		364 Days	
	Mean Strength (MPa)	Mean Strength (MPa)	Mean Strength (MPa)	Mean Strength (MPa)	Mean Strength (MPa)	Compressive Strength (MPa)	Mean Strength (MPa)	Compressive Strength (MPa)	Mean Strength (MPa)
E1	--	--	59.7	70.5	74.3	74.5 75.5 75.0	75.0	73.5 72.0 73.5	73.0
E2	--	34.7	54.2	57.7	61.8	65.0 66.0 66.5	65.8	65.0 66.0 66.0	65.7
E3	21.3	36.7	51.0	57.3	61.5	68.0 65.5 65.5	66.3	65.5 67.5 67.5	66.8
E4	21.0	27.2	33.7	38.0	40.3	42.5 43.5 44.0	43.3	45.0 46.5 43.0	44.8
E5	14.3	28.2	49.2	61.7	68.2	75.0 73.5 72.5	73.7	76.0 74.5 72.0	74.2
E6	46.8	55.5	57.7	62.5	68.3	71.0 69.0 72.0	70.7	72.5 72.0 73.5	72.7
E7	43.8	47.5	49.3	54.5	55.5	61.0 61.5 60.0	60.8	64.0 62.5 64.0	63.5
Note:	The details of the individual cube strengths of concrete mix between the ages of 3, 7 28, 56 and 91 days under the various curing environments are given in the interim report (Leung et al 2009).								

Table 13 - Compressive Strength of Concrete Mix M6/35C under Various Curing Environments

Curing Environment	Age at Test								
	3 Days	7 Days	28 Days	56 Days	91 Days	182 Days		364 Days	
	Mean Strength (MPa)	Mean Strength (MPa)	Mean Strength (MPa)	Mean Strength (MPa)	Mean Strength (MPa)	Compressive Strength (MPa)	Mean Strength (MPa)	Compressive Strength (MPa)	Mean Strength (MPa)
E1	--	--	58.8	68.8	77.5	74.0 76.5 77.0	75.8	77.0 77.0 74.0	76.0
E2	--	38.2	58.5	61.5	68.8	69.0 68.5 71.5	69.7	70.0 69.0 69.0	69.3
E3	24.3	43.2	55.2	57.7	63.5	64.0 63.5 65.0	64.2	61.5 64.0 62.5	62.7
E4	23.5	29.3	34.5	36.2	42.5	42.5 45.0 44.0	43.8	46.0 44.5 41.5	44.0
E5	16.3	30.7	49.3	57.5	67.8	62.0 61.5 64.0	62.5	73.5 72.5 69.5	71.8
E6	45.0	55.5	57.7	58.0	65.5	67.0 67.0 69.0	67.7	72.0 67.0 68.5	69.2
E7	44.7	51.7	52.0	54.2	58.8	74.0 71.0 69.0	71.3	64.0 61.0 63.0	62.7
Note:	The details of the individual cube strengths of concrete mix between the ages of 3, 7 28, 56 and 91 days under the various curing environments are given in the interim report (Leung et al 2009).								

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Table 14 - Compressive Strength of Concrete Mix M7/35C under Various Curing Environments

Curing Environment	Age at Test								
	3 Days	7 Days	28 Days	56 Days	91 Days	182 Days		364 Days	
	Mean Strength (MPa)	Mean Strength (MPa)	Mean Strength (MPa)	Mean Strength (MPa)	Mean Strength (MPa)	Compressive Strength (MPa)	Mean Strength (MPa)	Compressive Strength (MPa)	Mean Strength (MPa)
E1	--	--	57.2	65.7	69.2	74.5 72.5 72.0	73.0	74.5 74.0 75.0	74.5
E2	--	36.3	56.7	58.8	62.2	68.0 68.5 66.5	67.7	68.5 68.5 67.0	68.0
E3	21.3	37.7	49.8	51.2	56.0	59.0 60.5 59.5	59.7	59.5 63.5 62.5	61.8
E4	22.0	27.7	36.0	38.2	43.5	45.0 45.0 45.5	45.2	46.0 48.0 43.5	45.8
E5	15.0	27.5	49.7	60.0	66.7	72.0 74.0 73.0	73.0	75.0 73.0 73.0	73.7
E6	45.3	53.2	55.7	57.8	59.8	64.0 66.0 66.0	65.3	65.0 64.0 66.5	65.2
E7	43.2	44.7	48.2	47.0	47.2	51.5 49.0 50.0	50.2	54.0 53.0 53.0	53.3
Note:	The details of the individual cube strengths of concrete mix between the ages of 3, 7 28, 56 and 91 days under the various curing environments are given in the interim report (Leung et al 2009).								

Table 15 - Compressive Strength of Concrete Mix M8/35C under Various Curing Environments

Curing Environment	Age at Test								
	3 Days	7 Days	28 Days	56 Days	91 Days	182 Days		364 Days	
	Mean Strength (MPa)	Mean Strength (MPa)	Mean Strength (MPa)	Mean Strength (MPa)	Mean Strength (MPa)	Compressive Strength (MPa)	Mean Strength (MPa)	Compressive Strength (MPa)	Mean Strength (MPa)
E1	--	--	53.3	61.7	66.2	70.5 70.0 69.5	70.0	72.0 65.0 68.0	68.3
E2	--	32.8	51.7	54.0	58.2	60.0 61.5 60.0	60.5	59.0 60.0 62.0	60.3
E3	19.7	34.3	47.0	49.5	53.3	55.0 57.0 54.0	55.3	59.5 59.5 59.0	59.3
E4	19.8	25.7	34.2	32.2	34.3	34.5 36.5 35.0	35.3	35.0 36.0 35.5	35.5
E5	11.3	23.2	44.3	53.7	60.3	67.0 68.0 69.0	68.0	69.0 67.5 67.5	68.0
E6	41.7	51.0	50.5	54.3	56.2	59.0 60.5 57.5	59.0	58.0 58.0 56.5	57.5
E7	40.2	42.0	42.7	44.8	46.2	48.0 48.5 48.0	48.2	48.0 51.0 48.0	49.0
Note:	The details of the individual cube strengths of concrete mix between the ages of 3, 7 28, 56 and 91 days under the various curing environments are given in the interim report (Leung et al 2009).								

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Table 16 - Compressive Strength of Concrete Mix M9/35C under Various Curing Environments

Curing Environment	Age at Test								
	3 Days	7 Days	28 Days	56 Days	91 Days	182 Days		364 Days	
	Mean Strength (MPa)	Mean Strength (MPa)	Mean Strength (MPa)	Mean Strength (MPa)	Mean Strength (MPa)	Compressive Strength (MPa)	Mean Strength (MPa)	Compressive Strength (MPa)	Mean Strength (MPa)
E1	--	--	54.7	63.3	67.5	68.5 72.0 70.0	70.2	66.5 70.5 71.0	69.3
E2	--	34.0	48.7	54.5	59.2	64.5 64.5 61.5	63.5	65.5 67.0 65.5	66.0
E3	23.2	35.5	46.8	50.2	54.5	57.5 57.5 57.5	57.5	59.0 60.5 58.5	59.3
E4	21.5	25.3	29.5	32.2	35.0	38.0 39.5 38.5	38.7	40.5 40.5 39.0	40.0
E5	15.5	28.3	44.3	54.7	61.8	65.0 70.5 67.5	67.7	72.0 71.5 70.5	71.3
E6	41.5	53.2	51.8	57.2	56.8	56.5 56.0 57.5	56.7	59.0 62.0 58.0	59.7
E7	42.7	44.8	42.7	47.8	46.3	46.5 48.0 48.5	47.7	49.0 50.5 48.5	49.3
Note:	The details of the individual cube strengths of concrete mix between the ages of 3, 7 28, 56 and 91 days under the various curing environments are given in the interim report (Leung et al 2009).								

Table 17 - Compressive Strength of Concrete Mix M10/45C under Various Curing Environments

Curing Environment	Age at Test								
	3 Days	7 Days	28 Days	56 Days	91 Days	182 Days		364 Days	
	Mean Strength (MPa)	Mean Strength (MPa)	Mean Strength (MPa)	Mean Strength (MPa)	Mean Strength (MPa)	Compressive Strength (MPa)	Mean Strength (MPa)	Compressive Strength (MPa)	Mean Strength (MPa)
E1	--	--	60.8	72.0	74.8	73.5 72.5 71.5	72.5	63.5 59.5 58.0	60.3
E2	--	43.2	60.2	64.8	70.0	64.0 67.0 65.5	65.5	55.5 52.5 60.0	56.0
E3	28.0	42.7	55.5	60.3	62.3	61.0 62.0 61.5	61.5	64.0 63.5 63.0	63.5
E4	27.3	34.2	40.5	47.0	48.8	49.0 49.5 48.5	49.0	49.0 49.5 48.5	49.0
E5	22.3	36.8	58.0	69.3	74.7	72.5 72.0 71.5	72.0	73.5 74.0 72.5	73.3
E6	42.5	52.8	59.0	68.8	73.5	67.5 72.0 73.0	70.8	72.5 75.5 71.5	73.2
E7	41.2	45.8	47.8	56.2	61.0	63.5 63.0 63.5	63.3	59.0 62.5 60.0	60.5
Note:	The details of the individual cube strengths of concrete mix between the ages of 3, 7 28, 56 and 91 days under the various curing environments are given in the interim report (Leung et al 2009).								

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Table 18 - Compressive Strength of Concrete Mix M11/45C under Various Curing Environments

Curing Environment	Age at Test								
	3 Days	7 Days	28 Days	56 Days	91 Days	182 Days		364 Days	
	Mean Strength (MPa)	Mean Strength (MPa)	Mean Strength (MPa)	Mean Strength (MPa)	Mean Strength (MPa)	Compressive Strength (MPa)	Mean Strength (MPa)	Compressive Strength (MPa)	Mean Strength (MPa)
E1	--	--	63.3	73.2	73.5	76.5 74.5 75.5	75.5	79.0 77.5 76.5	77.7
E2	--	40.5	60.7	64.3	66.3	65.0 69.0 69.5	67.8	72.0 72.5 71.5	72.0
E3	25.2	43.8	54.2	59.7	60.5	62.5 65.5 64.5	64.2	67.5 68.0 65.0	66.8
E4	25.7	32.2	42.0	44.5	51.0	48.5 51.0 51.0	50.2	50.5 53.5 52.5	52.2
E5	17.5	31.0	55.3	67.7	73.5	76.5 77.5 73.5	75.8	75.5 77.5 75.5	76.2
E6	47.0	51.8	66.5	68.3	78.0	72.0 73.0 71.5	72.2	76.0 77.0 75.0	76.0
E7	45.7	50.3	55.2	62.5	65.5	63.5 57.0 65.5	62.0	65.0 65.5 65.5	65.3

Note: The details of the individual cube strengths of concrete mix between the ages of 3, 7 28, 56 and 91 days under the various curing environments are given in the interim report (Leung et al 2009).

Table 19 - Compressive Strength of Concrete Mix M12/45C under Various Curing Environments

Curing Environment	Age at Test								
	3 Days	7 Days	28 Days	56 Days	91 Days	182 Days		364 Days	
	Mean Strength (MPa)	Mean Strength (MPa)	Mean Strength (MPa)	Mean Strength (MPa)	Mean Strength (MPa)	Compressive Strength (MPa)	Mean Strength (MPa)	Compressive Strength (MPa)	Mean Strength (MPa)
E1	--	--	71.0	79.5	89.7	88.0 88.5 91.0	89.2	87.5 92.0 90.5	90.0
E2	--	46.7	66.0	72.7	77.2	79.5 82.5 79.0	80.3	79.5 83.5 78.5	80.5
E3	29.3	46.5	63.8	71.2	76.8	77.5 78.5 79.0	78.3	82.0 83.5 82.5	82.7
E4	28.2	34.7	43.2	46.5	51.5	51.5 56.0 53.5	53.7	53.5 56.0 54.5	54.7
E5	18.2	36.2	58.3	71.7	80.7	86.0 84.5 86.0	85.5	81.0 85.5 86.0	84.2
E6	56.8	68.3	71.7	78.2	79.7	81.5 81.5 84.5	82.5	81.0 76.0 83.0	80.0
E7	59.5	61.7	64.8	67.7	72.0	73.5 77.5 75.0	75.3	76.0 74.5 76.5	75.7

Note: The details of the individual cube strengths of concrete mix between the ages of 3, 7 28, 56 and 91 days under the various curing environments are given in the interim report (Leung et al 2009).

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Table 20 - Compressive Strength of Concrete Mix M13/45C under Various Curing Environments

Curing Environment	Age at Test: 3 Days	7 Days	28 Days	56 Days	91 Days	182 Days		364 Days	
	Mean Strength (MPa)	Mean Strength (MPa)	Mean Strength (MPa)	Mean Strength (MPa)	Mean Strength (MPa)	Compressive Strength (MPa)	Mean Strength (MPa)	Compressive Strength (MPa)	Mean Strength (MPa)
E1	--	--	69.2	78.0	86.2	81.5 82.0 80.5	81.3	82.5 84.0 84.5	83.7
E2	--	43.3	63.5	69.0	77.7	77.0 77.5 76.5	77.0	78.0 77.5 76.0	77.2
E3	29.5	50.3	64.5	65.2	72.8	72.5 73.5 75.0	73.7	71.0 72.5 69.5	71.0
E4	28.5	31.3	40.5	41.7	48.2	50.0 52.0 47.0	49.7	50.0 51.0 46.5	49.2
E5	18.8	37.0	53.7	68.8	78.0	83.5 81.0 79.0	81.2	83.0 81.0 80.0	81.3
E6	54.7	66.3	66.0	67.7	72.3	77.0 76.5 74.5	76.0	76.0 77.5 73.0	75.5
E7	55.8	60.8	63.8	65.0	66.8	69.5 69.5 71.0	70.0	70.5 71.0 71.5	71.0

Note: The details of the individual cube strengths of concrete mix between the ages of 3, 7 28, 56 and 91 days under the various curing environments are given in the interim report (Leung et al 2009).

Table 21 - Compressive Strength of Concrete Mix M14/45C under Various Curing Environments

Curing Environment	Age at Test: 3 Days	7 Days	28 Days	56 Days	91 Days	182 Days		364 Days	
	Mean Strength (MPa)	Mean Strength (MPa)	Mean Strength (MPa)	Mean Strength (MPa)	Mean Strength (MPa)	Compressive Strength (MPa)	Mean Strength (MPa)	Compressive Strength (MPa)	Mean Strength (MPa)
E1	--	--	74.5	83.3	87.3	86.5 89.0 88.0	87.8	88.5 90.0 94.0	90.8
E2	--	49.3	70.8	73.2	76.2	79.0 82.0 82.5	81.2	83.0 83.0 83.0	83.0
E3	31.0	51.5	67.0	64.7	70.2	75.5 79.0 76.0	76.8	75.0 79.0 79.5	77.8
E4	30.0	37.5	50.3	49.0	52.8	59.0 59.0 57.5	58.5	60.0 59.5 59.0	59.5
E5	21.0	38.0	62.2	75.7	81.5	93.0 88.5 88.5	90.0	89.5 86.5 87.5	87.8
E6	65.5	72.3	73.3	74.8	79.5	79.5 78.0 78.5	78.7	81.0 80.5 75.5	79.0
E7	58.3	62.2	64.2	63.5	64.8	71.5 67.5 67.5	68.8	67.5 64.5 68.0	66.7

Note: The details of the individual cube strengths of concrete mix between the ages of 3, 7 28, 56 and 91 days under the various curing environments are given in the interim report (Leung et al 2009).

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Table 22 - Compressive Strength of Concrete Mix M15/45C under Various Curing Environments

Curing Environment	Age at Test								
	3 Days	7 Days	28 Days	56 Days	91 Days	182 Days		364 Days	
	Mean Strength (MPa)	Mean Strength (MPa)	Mean Strength (MPa)	Mean Strength (MPa)	Mean Strength (MPa)	Compressive Strength (MPa)	Mean Strength (MPa)	Compressive Strength (MPa)	Mean Strength (MPa)
E1	--	--	71.7	85.3	90.0	89.0 92.0 90.0	90.3	94.0 91.5 89.5	91.7
E2	--	48.5	70.3	74.2	77.7	79.5 82.5 79.5	80.5	80.0 80.5 79.5	80.0
E3	33.0	47.7	65.5	68.0	74.2	76.5 75.5 74.5	75.5	76.0 78.5 76.5	77.0
E4	32.0	37.5	47.8	47.8	50.5	52.5 53.5 50.5	52.2	52.5 54.5 50.5	52.5
E5	18.7	36.0	60.2	69.7	83.2	87.5 93.5 94.0	91.7	90.0 91.0 89.0	90.0
E6	64.3	73.5	70.7	75.3	76.0	76.5 79.0 77.5	77.7	78.5 74.5 77.0	76.7
E7	59.8	61.0	60.8	60.5	63.7	68.0 67.0 68.5	67.8	65.5 66.0 63.5	65.0
Note:	The details of the individual cube strengths of concrete mix between the ages of 3, 7 28, 56 and 91 days under the various curing environments are given in the interim report (Leung et al 2009).								

Table 23 - Compressive Strength of Concrete Mix M16/45C under Various Curing Environments

Curing Environment	Age at Test								
	3 Days	7 Days	28 Days	56 Days	91 Days	182 Days		364 Days	
	Mean Strength (MPa)	Mean Strength (MPa)	Mean Strength (MPa)	Mean Strength (MPa)	Mean Strength (MPa)	Compressive Strength (MPa)	Mean Strength (MPa)	Compressive Strength (MPa)	Mean Strength (MPa)
E1	--	--	71.8	83.3	87.0	88.0 88.5 88.5	88.3	88.5 88.5 94.0	90.3
E2	--	45.5	64.3	72.5	77.5	77.5 80.5 81.0	79.7	79.5 82.0 80.5	80.7
E3	34.0	49.5	62.3	66.5	73.0	75.0 71.0 72.0	72.7	73.0 74.0 76.0	74.3
E4	33.0	33.8	43.5	46.7	51.5	52.5 57.0 55.5	55.0	54.5 54.0 54.5	54.3
E5	24.3	38.3	59.2	71.5	78.0	87.5 88.0 87.0	87.5	84.5 88.0 89.5	87.3
E6	55.2	69.5	72.2	73.0	74.3	80.0 81.0 77.5	79.5	78.5 78.0 77.0	77.8
E7	60.2	60.8	62.5	64.0	65.8	68.0 65.5 66.5	66.7	66.0 70.0 65.5	67.2
Note:	The details of the individual cube strengths of concrete mix between the ages of 3, 7 28, 56 and 91 days under the various curing environments are given in the interim report (Leung et al 2009).								

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Table 24 - Compressive Strength of Concrete Mix M3/35S under Various Curing Environments

Curing Environment	Age at Test								
	3 Days	7 Days	28 Days	56 Days	91 Days	182 Days		364 Days	
	Mean Strength (MPa)	Mean Strength (MPa)	Mean Strength (MPa)	Mean Strength (MPa)	Mean Strength (MPa)	Compressive Strength (MPa)	Mean Strength (MPa)	Compressive Strength (MPa)	Mean Strength (MPa)
E1	--	--	56.3	65.5	67.5	66.0 68.5 69.0	67.8	67.5 69.5 70.5	69.2
E2	--	35.8	55.8	58.3	59.7	64.0 63.5 61.5	63.0	63.0 64.5 62.0	63.2
E3	23.8	37.2	51.8	55.5	53.7	58.5 55.5 59.0	57.7	57.5 58.5 58.0	58.0
E4	23.0	31.7	42.5	42.5	41.7	45.5 47.0 45.0	45.8	48.0 49.0 47.0	48.0
E5	18.3	25.7	53.5	61.5	62.3	68.0 65.0 64.0	65.7	67.0 67.5 63.0	65.8
E6	31.5	47.5	54.5	62.2	62.5	64.5 65.0 64.5	64.7	63.0 65.5 65.0	64.5
E7	33.7	37.5	39.8	46.8	49.2	54.0 54.5 53.5	54.0	55.5 54.0 53.5	54.3
Note:	The details of the individual cube strengths of concrete mix between the ages of 3, 7 28, 56 and 91 days under the various curing environments are given in the interim report (Leung et al 2009).								

Table 25 - Compressive Strength of Concrete Mix M4/35S under Various Curing Environments

Curing Environment	Age at Test								
	3 Days	7 Days	28 Days	56 Days	91 Days	182 Days		364 Days	
	Mean Strength (MPa)	Mean Strength (MPa)	Mean Strength (MPa)	Mean Strength (MPa)	Mean Strength (MPa)	Compressive Strength (MPa)	Mean Strength (MPa)	Compressive Strength (MPa)	Mean Strength (MPa)
E1	--	--	51.3	57.3	62.5	65.0 64.0 66.0	65.0	60.5 60.0 60.0	60.2
E2	--	29.8	48.8	50.3	52.5	54.5 56.0 56.5	55.7	53.0 56.0 51.0	53.3
E3	18.5	33.3	45.8	46.2	46.8	51.5 55.0 53.5	53.3	54.0 55.0 55.5	54.8
E4	18.8	26.5	32.8	36.3	38.0	41.5 44.0 41.5	42.3	43.5 43.5 43.5	43.5
E5	13.8	23.8	44.0	55.0	59.7	61.5 62.5 61.0	61.7	59.0 62.0 63.5	61.5
E6	32.8	46.7	50.8	60.2	57.5	65.0 65.0 65.0	65.0	59.0 60.0 59.5	59.5
E7	33.3	36.3	39.5	47.2	48.0	53.5 52.5 53.0	53.0	52.0 54.0 53.5	53.2
Note:	The details of the individual cube strengths of concrete mix between the ages of 3, 7 28, 56 and 91 days under the various curing environments are given in the interim report (Leung et al 2009).								

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Table 26 - Compressive Strength of Concrete Mix M5/35S under Various Curing Environments

Curing Environment	Age at Test								
	3 Days	7 Days	28 Days	56 Days	91 Days	182 Days		364 Days	
	Mean Strength (MPa)	Mean Strength (MPa)	Mean Strength (MPa)	Mean Strength (MPa)	Mean Strength (MPa)	Compressive Strength (MPa)	Mean Strength (MPa)	Compressive Strength (MPa)	Mean Strength (MPa)
E1	--	--	51.3	59.3	63.0	64.0 66.0 66.0	65.3	62.5 65.5 67.5	65.2
E2	--	28.8	46.2	51.5	51.8	56.0 57.5 55.0	56.2	58.0 58.0 56.0	57.3
E3	17.5	28.3	41.7	44.8	45.7	50.5 53.5 50.0	51.3	52.5 55.0 50.5	52.7
E4	17.5	22.3	32.3	32.2	31.8	35.0 35.5 32.0	34.2	36.0 37.0 33.5	35.5
E5	11.2	21.2	41.5	51.2	55.3	59.0 61.5 61.0	60.5	59.5 64.0 62.5	62.0
E6	34.2	47.0	49.2	54.2	57.5	61.0 62.5 58.5	60.7	69.5 62.0 59.0	63.5
E7	35.5	39.8	44.2	47.5	50.3	54.0 53.5 54.5	54.0	56.5 56.0 54.5	55.7
Note:	The details of the individual cube strengths of concrete mix between the ages of 3, 7 28, 56 and 91 days under the various curing environments are given in the interim report (Leung et al 2009).								

Table 27 - Compressive Strength of Concrete Mix M6/35S under Various Curing Environments

Curing Environment	Age at Test								
	3 Days	7 Days	28 Days	56 Days	91 Days	182 Days		364 Days	
	Mean Strength (MPa)	Mean Strength (MPa)	Mean Strength (MPa)	Mean Strength (MPa)	Mean Strength (MPa)	Compressive Strength (MPa)	Mean Strength (MPa)	Compressive Strength (MPa)	Mean Strength (MPa)
E1	--	--	57.8	66.5	72.7	73.0 73.5 75.5	74.0	73.0 75.5 74.0	74.2
E2	--	37.5	53.2	58.2	65.3	66.5 64.0 65.0	65.2	65.5 67.5 67.5	66.8
E3	23.8	35.2	49.7	52.8	58.2	65.5 62.5 62.0	63.3	66.0 64.0 64.0	64.7
E4	23.8	28.0	38.3	37.5	42.8	43.0 45.0 45.0	44.3	47.0 47.0 47.0	47.0
E5	16.0	28.7	47.2	57.5	63.7	70.5 67.0 70.5	69.3	66.5 68.5 68.5	67.8
E6	40.5	56.0	59.8	61.0	64.8	66.5 70.0 68.0	68.2	69.0 70.5 66.5	68.7
E7	44.5	51.7	50.2	55.7	62.2	62.0 63.5 61.5	62.3	59.5 61.5 61.5	60.8
Note:	The details of the individual cube strengths of concrete mix between the ages of 3, 7 28, 56 and 91 days under the various curing environments are given in the interim report (Leung et al 2009).								

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Table 28 - Compressive Strength of Concrete Mix M7/35S under Various Curing Environments

Curing Environment	Age at Test								
	3 Days	7 Days	28 Days	56 Days	91 Days	182 Days		364 Days	
	Mean Strength (MPa)	Mean Strength (MPa)	Mean Strength (MPa)	Mean Strength (MPa)	Mean Strength (MPa)	Compressive Strength (MPa)	Mean Strength (MPa)	Compressive Strength (MPa)	Mean Strength (MPa)
E1	--	--	54.0	61.2	63.8	66.5 70.0 70.0	68.8	65.0 67.0 67.5	66.5
E2	--	28.7	46.8	53.5	53.2	56.0 60.5 59.0	58.5	60.0 61.5 57.5	59.7
E3	17.2	33.3	42.5	48.2	47.5	51.5 52.5 53.0	52.3	51.0 55.5 52.5	53.0
E4	17.8	24.5	33.7	36.3	36.3	38.5 41.5 41.0	40.3	40.5 43.0 41.5	41.7
E5	12.7	22.2	44.2	54.8	59.8	67.5 67.5 67.5	67.5	67.5 69.5 64.5	67.2
E6	38.0	48.2	48.5	51.7	53.3	57.0 60.0 57.5	58.2	57.5 59.0 57.0	57.8
E7	36.5	39.5	41.0	42.7	45.0	50.0 47.5 48.0	48.5	48.5 51.5 53.0	51.0
Note:	The details of the individual cube strengths of concrete mix between the ages of 3, 7 28, 56 and 91 days under the various curing environments are given in the interim report (Leung et al 2009).								

Table 29 - Compressive Strength of Concrete Mix M8/35S under Various Curing Environments

Curing Environment	Age at Test								
	3 Days	7 Days	28 Days	56 Days	91 Days	182 Days		364 Days	
	Mean Strength (MPa)	Mean Strength (MPa)	Mean Strength (MPa)	Mean Strength (MPa)	Mean Strength (MPa)	Compressive Strength (MPa)	Mean Strength (MPa)	Compressive Strength (MPa)	Mean Strength (MPa)
E1	--	--	57.8	65.5	70.2	74.0 76.5 75.0	75.2	73.0 71.0 72.0	72.0
E2	--	36.2	52.8	57.5	61.0	66.0 67.0 66.0	66.3	66.0 67.5 65.0	66.2
E3	19.3	33.2	44.7	48.5	56.3	60.5 63.5 59.0	61.0	63.5 66.0 64.5	64.7
E4	19.3	28.7	36.5	37.5	38.8	46.0 46.0 45.0	45.7	42.0 49.0 48.0	46.3
E5	11.7	25.2	46.0	48.5	61.7	71.0 74.0 71.5	72.2	70.5 70.0 71.5	70.7
E6	41.7	52.5	53.0	57.7	57.7	60.0 61.0 60.5	60.5	57.5 59.0 57.0	57.8
E7	42.7	43.2	45.2	46.3	48.7	47.0 51.0 49.0	49.0	49.5 52.5 51.0	51.0
Note:	The details of the individual cube strengths of concrete mix between the ages of 3, 7 28, 56 and 91 days under the various curing environments are given in the interim report (Leung et al 2009).								

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Table 30 - Compressive Strength of Concrete Mix M9/35S under Various Curing Environments

Curing Environment	Age at Test								
	3 Days	7 Days	28 Days	56 Days	91 Days	182 Days		364 Days	
	Mean Strength (MPa)	Mean Strength (MPa)	Mean Strength (MPa)	Mean Strength (MPa)	Mean Strength (MPa)	Compressive Strength (MPa)	Mean Strength (MPa)	Compressive Strength (MPa)	Mean Strength (MPa)
E1	--	--	56.8	67.0	69.5	71.5 75.5 72.0	73.0	70.5 75.5 78.0	74.7
E2	--	34.7	52.0	56.8	61.0	65.5 70.5 66.5	67.5	70.5 69.5 68.0	69.3
E3	21.3	35.0	49.0	53.5	55.0	62.5 66.5 65.0	64.7	67.5 67.0 64.0	66.2
E4	19.8	25.0	33.7	37.3	37.8	42.0 42.0 40.5	41.5	42.0 44.0 43.0	43.0
E5	12.8	25.3	44.0	55.5	60.0	67.0 68.5 69.0	68.2	69.5 68.5 69.5	69.2
E6	35.3	55.0	54.0	53.5	56.7	58.0 60.5 59.0	59.2	69.5 62.0 62.5	64.7
E7	41.8	43.2	44.7	47.7	47.8	46.0 49.0 49.5	48.2	52.0 49.0 49.0	50.0
Note:	The details of the individual cube strengths of concrete mix between the ages of 3, 7 28, 56 and 91 days under the various curing environments are given in the interim report (Leung et al 2009).								

Table 31 - Compressive Strength of Concrete Mix M10/45S under Various Curing Environments

Curing Environment	Age at Test								
	3 Days	7 Days	28 Days	56 Days	91 Days	182 Days		364 Days	
	Mean Strength (MPa)	Mean Strength (MPa)	Mean Strength (MPa)	Mean Strength (MPa)	Mean Strength (MPa)	Compressive Strength (MPa)	Mean Strength (MPa)	Compressive Strength (MPa)	Mean Strength (MPa)
E1	--	--	66.0	74.3	78.3	78.5 78.0 77.5	78.0	76.0 82.5 81.5	80.0
E2	--	43.5	64.5	66.7	70.0	77.0 73.0 70.5	73.5	73.0 75.5 76.5	75.0
E3	29.8	45.3	60.8	60.7	65.0	66.5 70.5 65.0	67.3	68.5 68.0 69.0	68.5
E4	27.8	35.7	49.8	48.7	50.5	54.0 56.5 53.5	54.7	55.0 58.0 54.5	55.8
E5	22.2	30.7	62.2	69.0	73.8	75.0 76.5 76.5	76.0	76.5 80.0 75.5	77.3
E6	39.5	55.2	63.2	71.0	74.2	73.0 76.0 73.0	74.0	77.0 77.5 79.5	78.0
E7	42.8	47.2	51.2	58.0	63.7	59.0 61.0 61.0	60.3	63.5 62.5 64.5	63.5
Note:	The details of the individual cube strengths of concrete mix between the ages of 3, 7 28, 56 and 91 days under the various curing environments are given in the interim report (Leung et al 2009).								

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Table 32 - Compressive Strength of Concrete Mix M11/45S under Various Curing Environments

Curing Environment	Age at Test								
	3 Days	7 Days	28 Days	56 Days	91 Days	182 Days		364 Days	
	Mean Strength (MPa)	Mean Strength (MPa)	Mean Strength (MPa)	Mean Strength (MPa)	Mean Strength (MPa)	Compressive Strength (MPa)	Mean Strength (MPa)	Compressive Strength (MPa)	Mean Strength (MPa)
E1	--	--	60.5	68.0	73.2	78.5 80.0 79.0	79.2	76.0 75.5 76.5	76.0
E2	--	37.7	56.8	59.5	62.7	68.5 68.5 68.5	68.5	71.0 69.5 67.5	69.3
E3	22.8	41.5	51.8	56.0	56.0	65.0 65.5 64.5	65.0	64.0 63.5 63.5	63.7
E4	23.8	30.0	41.0	41.2	44.2	50.5 51.0 50.0	50.5	52.5 54.0 49.5	52.0
E5	17.0	27.7	51.3	62.0	65.8	70.5 73.5 71.5	71.8	69.5 71.0 69.5	70.0
E6	41.8	56.0	59.0	67.8	67.8	71.0 71.5 72.5	71.7	69.5 72.5 73.5	71.8
E7	40.0	46.2	51.0	57.8	61.2	63.5 64.0 62.0	63.2	65.5 64.0 67.0	65.5

Note: The details of the individual cube strengths of concrete mix between the ages of 3, 7 28, 56 and 91 days under the various curing environments are given in the interim report (Leung et al 2009).

Table 33 - Compressive Strength of Concrete Mix M12/45S under Various Curing Environments

Curing Environment	Age at Test								
	3 Days	7 Days	28 Days	56 Days	91 Days	182 Days		364 Days	
	Mean Strength (MPa)	Mean Strength (MPa)	Mean Strength (MPa)	Mean Strength (MPa)	Mean Strength (MPa)	Compressive Strength (MPa)	Mean Strength (MPa)	Compressive Strength (MPa)	Mean Strength (MPa)
E1	--	--	61.2	73.3	75.0	80.0 80.5 79.0	79.8	78.0 79.0 75.5	77.5
E2	--	37.3	56.5	61.2	63.0	68.0 67.5 68.5	68.0	69.0 70.0 69.0	69.3
E3	22.7	36.7	52.7	59.3	57.3	61.5 65.0 65.0	63.8	68.5 64.5 64.5	65.8
E4	20.7	28.3	41.0	44.2	40.7	44.5 44.0 44.5	44.3	46.5 47.0 46.0	46.5
E5	13.7	26.8	49.7	60.7	65.0	69.0 70.5 71.0	70.2	72.0 73.5 72.5	72.7
E6	44.8	62.7	62.5	66.8	70.3	72.5 72.0 70.5	71.7	74.5 75.0 72.0	73.8
E7	48.3	54.0	56.0	62.0	62.5	64.5 63.5 63.5	63.8	65.5 69.5 70.5	68.5

Note: The details of the individual cube strengths of concrete mix between the ages of 3, 7 28, 56 and 91 days under the various curing environments are given in the interim report (Leung et al 2009).

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Table 34 - Compressive Strength of Concrete Mix M13/45S under Various Curing Environments

Curing Environment	Age at Test								
	3 Days	7 Days	28 Days	56 Days	91 Days	182 Days		364 Days	
	Mean Strength (MPa)	Mean Strength (MPa)	Mean Strength (MPa)	Mean Strength (MPa)	Mean Strength (MPa)	Compressive Strength (MPa)	Mean Strength (MPa)	Compressive Strength (MPa)	Mean Strength (MPa)
E1	--	--	68.5	79.0	81.2	80.5 83.0 82.0	81.8	83.5 84.5 86.0	84.7
E2	--	42.7	63.2	68.2	71.2	76.5 79.0 76.0	77.2	77.5 78.5 74.5	76.8
E3	31.2	41.0	58.5	59.5	64.7	72.0 74.0 71.0	72.3	73.0 73.5 77.0	74.5
E4	28.8	31.3	44.0	46.8	48.3	53.0 50.0 50.5	51.2	55.0 53.0 53.0	53.7
E5	20.3	32.7	54.0	67.0	74.0	80.0 80.5 76.0	78.8	78.0 81.5 82.5	80.7
E6	46.8	66.5	67.8	71.0	76.8	77.0 75.0 79.0	77.0	81.5 78.0 77.0	78.8
E7	53.8	63.5	64.2	68.0	68.5	71.0 70.0 68.0	69.7	65.5 74.0 72.0	70.5
Note:	The details of the individual cube strengths of concrete mix between the ages of 3, 7 28, 56 and 91 days under the various curing environments are given in the interim report (Leung et al 2009).								

Table 35 - Compressive Strength of Concrete Mix M14/45S under Various Curing Environments

Curing Environment	Age at Test								
	3 Days	7 Days	28 Days	56 Days	91 Days	182 Days		364 Days	
	Mean Strength (MPa)	Mean Strength (MPa)	Mean Strength (MPa)	Mean Strength (MPa)	Mean Strength (MPa)	Compressive Strength (MPa)	Mean Strength (MPa)	Compressive Strength (MPa)	Mean Strength (MPa)
E1	--	--	66.0	75.7	80.5	80.0 81.0 82.5	81.2	82.0 82.0 85.5	83.2
E2	--	39.2	59.3	63.2	64.7	68.5 73.0 72.0	71.2	74.5 75.5 74.5	74.8
E3	24.5	45.2	54.0	59.5	58.5	65.0 69.5 63.5	66.0	67.5 69.0 65.5	67.3
E4	24.5	32.8	43.2	46.0	47.5	51.5 53.0 53.0	52.5	54.5 53.5 53.5	53.8
E5	17.0	30.7	54.2	65.0	70.0	79.0 80.0 81.5	80.2	76.5 81.0 80.5	79.3
E6	50.5	61.0	63.7	66.7	68.5	71.5 70.0 71.5	71.0	73.0 74.5 75.5	74.3
E7	50.3	54.2	54.3	55.8	58.7	63.0 61.5 61.5	62.0	62.0 64.0 62.5	62.8
Note:	The details of the individual cube strengths of concrete mix between the ages of 3, 7 28, 56 and 91 days under the various curing environments are given in the interim report (Leung et al 2009).								

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Table 36 - Compressive Strength of Concrete Mix M15/45S under Various Curing Environments

Curing Environment	Age at Test								
	3 Days	7 Days	28 Days	56 Days	91 Days	182 Days		364 Days	
	Mean Strength (MPa)	Mean Strength (MPa)	Mean Strength (MPa)	Mean Strength (MPa)	Mean Strength (MPa)	Compressive Strength (MPa)	Mean Strength (MPa)	Compressive Strength (MPa)	Mean Strength (MPa)
E1	--	--	61.0	71.8	73.0	78.0 77.0 79.5	78.2	84.5 82.5 82.0	83.0
E2	--	38.7	56.3	61.8	62.7	68.5 68.5 68.0	68.3	69.0 73.0 67.5	69.8
E3	20.8	36.8	48.8	55.8	55.8	62.5 64.0 63.5	63.3	66.5 65.5 57.0	63.0
E4	21.0	29.8	38.5	38.2	43.3	43.5 47.5 44.0	45.0	43.5 48.0 48.0	46.5
E5	12.5	26.5	48.0	59.0	69.3	76.0 76.0 73.0	75.0	70.5 78.5 77.0	75.3
E6	46.0	58.0	59.2	65.5	64.5	67.5 68.0 64.0	66.5	67.5 65.0 68.5	67.0
E7	46.5	48.2	47.8	49.5	53.8	52.0 56.0 52.5	53.5	54.0 55.0 57.5	55.5
Note:	The details of the individual cube strengths of concrete mix between the ages of 3, 7 28, 56 and 91 days under the various curing environments are given in the interim report (Leung et al 2009).								

Table 37 - Compressive Strength of Concrete Mix M16/45S under Various Curing Environments

Curing Environment	Age at Test								
	3 Days	7 Days	28 Days	56 Days	91 Days	182 Days		364 Days	
	Mean Strength (MPa)	Mean Strength (MPa)	Mean Strength (MPa)	Mean Strength (MPa)	Mean Strength (MPa)	Compressive Strength (MPa)	Mean Strength (MPa)	Compressive Strength (MPa)	Mean Strength (MPa)
E1	--	--	68.8	80.5	81.5	86.5 89.0 87.0	87.5	86.5 84.0 88.5	86.3
E2	--	43.8	61.8	70.2	71.2	75.0 79.5 77.5	77.3	76.0 82.5 80.5	79.7
E3	29.3	44.0	55.8	64.8	65.7	72.0 75.0 72.5	73.2	74.5 75.0 74.0	74.5
E4	24.7	32.3	43.2	47.0	48.7	52.5 52.5 49.5	51.5	51.5 54.5 51.5	52.5
E5	15.8	31.7	52.7	67.2	73.3	72.5 76.0 81.0	76.5	79.0 80.5 83.0	80.8
E6	45.2	64.5	67.2	72.0	73.2	74.5 76.5 77.0	76.0	75.0 75.0 73.5	74.5
E7	55.2	56.3	57.8	59.8	60.7	61.0 63.0 63.0	62.3	60.0 60.5 60.5	60.3
Note:	The details of the individual cube strengths of concrete mix between the ages of 3, 7 28, 56 and 91 days under the various curing environments are given in the interim report (Leung et al 2009).								

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Table 38 - Mean Compressive Strength for Grade 35 Mixes (CRC)

Curing Environment	Age (days)	Grade 35 Concrete							
		M1	M3/35C	M4/35C	M5/35C	M6/35C	M7/35C	M8/35C	M9/35C
		0/100/0	30/70/0	50/50/0	70/30/0	80/20/0	47.5/47.5/5	67.5/27.5/5	75/20/5
E1 27°C water for 27 days then air curing	28	49.0	56.3	56.8	59.7	58.8	57.2	53.3	54.7
	56	57.5	62.5	67.0	70.5	68.8	65.7	61.7	63.3
	91	62.3	65.5	68.3	74.3	77.5	69.2	66.2	67.5
	182	62.5	65.7	67.5	75.0	75.8	73.0	70.0	70.2
	364	61.7	63.0	68.2	73.0	76.0	74.5	68.3	69.3
E2 27°C water for 7 days then air curing	7	36.2	40.2	35.0	34.7	38.2	36.3	32.8	34.0
	28	50.3	57.0	53.5	54.2	58.5	56.7	51.7	48.7
	56	51.7	60.8	58.3	57.7	61.5	58.8	54.0	54.5
	91	55.7	62.7	57.2	61.8	68.8	62.2	58.2	59.2
	182	56.3	59.8	61.5	65.8	69.7	67.7	60.5	63.5
	364	54.3	56.7	61.3	65.7	69.3	68.0	60.3	66.0
E3 27°C water for 3 days then air curing	3	28.8	26.2	21.7	21.3	24.3	21.3	19.7	23.2
	7	39.2	39.3	38.5	36.7	43.2	37.7	34.3	35.5
	28	48.7	52.7	49.7	51.0	55.2	49.8	47.0	46.8
	56	51.0	56.3	51.2	57.3	57.7	51.2	49.5	50.2
	91	55.7	56.0	53.0	61.5	63.5	56.0	53.3	54.5
	182	53.0	56.8	56.8	66.3	64.2	59.7	55.3	57.5
	364	53.7	51.7	59.0	66.8	62.7	61.8	59.3	59.3
E4 Air curing	3	27.3	26.8	22.3	21.0	23.5	22.0	19.8	21.5
	7	32.8	32.8	29.3	27.2	29.3	27.7	25.7	25.3
	28	38.5	40.3	38.3	33.7	34.5	36.0	34.2	29.5
	56	38.7	44.7	40.7	38.0	36.2	38.2	32.2	32.2
	91	43.8	44.7	42.8	40.3	42.5	43.5	34.3	35.0
	182	41.8	47.8	47.2	43.3	43.8	45.2	35.3	38.7
	364	43.2	46.7	48.7	44.8	44.0	45.8	35.5	40.0
E5 10°C water for 3 days followed by 20°C water for 24 days then air curing	3	23.8	20.5	16.3	14.3	16.3	15.0	11.3	15.5
	7	34.8	33.2	26.7	28.2	30.7	27.5	23.2	28.3
	28	50.0	55.0	51.5	49.2	49.3	49.7	44.3	44.3
	56	57.5	63.3	62.2	61.7	57.5	60.0	53.7	54.7
	91	61.7	66.2	66.3	68.2	67.8	66.7	60.3	61.8
	182	63.3	67.7	64.8	73.7	62.5	73.0	68.0	67.7
	364	63.0	61.7	68.0	74.2	71.8	73.7	68.0	71.3
E6 50°C water for 7 days followed by 27°C water for 20 days then air curing	3	31.8	38.3	40.7	46.8	45.0	45.3	41.7	41.5
	7	42.7	51.5	54.8	55.5	55.5	53.2	51.0	53.2
	28	49.8	56.0	57.2	57.7	57.7	55.7	50.5	51.8
	56	52.8	61.8	65.0	62.5	58.0	57.8	54.3	57.2
	91	55.7	66.0	68.8	68.3	65.5	59.8	56.2	56.8
	182	60.3	67.0	66.7	70.7	67.7	65.3	59.0	56.7
	364	61.7	58.0	69.2	72.7	69.2	65.2	57.5	59.7
E7 75°C water for 7 days followed by 27°C water for 20 days then air curing	3	33.8	37.3	37.3	43.8	44.7	43.2	40.2	42.7
	7	36.8	41.2	41.8	47.5	51.7	44.7	42.0	44.8
	28	38.0	43.0	44.0	49.3	52.0	48.2	42.7	42.7
	56	45.0	51.8	52.5	54.5	54.2	47.0	44.8	47.8
	91	48.2	53.3	56.7	55.5	58.8	47.2	46.2	46.3
	182	51.2	56.5	56.2	60.8	71.3	50.2	48.2	47.7
	364	50.7	46.7	56.7	63.5	62.7	53.3	49.0	49.3

Notes:
(1) The details of the concrete mixes and the curing environment are given in Table 5, 6 and 7 respectively. For easy reference, the proportions of GGBS/PC/SF in percentage are also given.
(2) The mean compressive strengths in this Table are taken from Tables 8 to 37 of this Report and are in units of MPa.

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Table 39 - Mean Compressive Strength for Grade 35 Mixes (SG)

Curing Environment	Age (days)	Grade 35 Concrete							
		M1	M3/35S	M4/35S	M5/35S	M6/35S	M7/35S	M8/35S	M9/35S
		0/100/0	30/70/0	50/50/0	70/30/0	80/20/0	47.5/47.5/5	67.5/27.5/5	75/20/5
E1 27°C water for 27 days then air curing	28	49.0	56.3	51.3	51.3	57.8	54.0	57.8	56.8
	56	57.5	65.5	57.3	59.3	66.5	61.2	65.5	67.0
	91	62.3	67.5	62.5	63.0	72.7	63.8	70.2	69.5
	182	62.5	67.8	65.0	65.3	74.0	68.8	75.2	73.0
	364	61.7	69.2	60.2	65.2	74.2	66.5	72.0	74.7
E2 27°C water for 7 days then air curing	7	36.2	35.8	29.8	28.8	37.5	28.7	36.2	34.7
	28	50.3	55.8	48.8	46.2	53.2	46.8	52.8	52.0
	56	51.7	58.3	50.3	51.5	58.2	53.5	57.5	56.8
	91	55.7	59.7	52.5	51.8	65.3	53.2	61.0	61.0
	182	56.3	63.0	55.7	56.2	65.2	58.5	66.3	67.5
	364	54.3	63.2	53.3	57.3	66.8	59.7	66.2	69.3
E3 27°C water for 3 days then air curing	3	28.8	23.8	18.5	17.5	23.8	17.2	19.3	21.3
	7	39.2	37.2	33.3	28.3	35.2	33.3	33.2	35.0
	28	48.7	51.8	45.8	41.7	49.7	42.5	44.7	49.0
	56	51.0	55.5	46.2	44.8	52.8	48.2	48.5	53.5
	91	55.7	53.7	46.8	45.7	58.2	47.5	56.3	55.0
	182	53.0	57.7	53.3	51.3	63.3	52.3	61.0	64.7
	364	53.7	58.0	54.8	52.7	64.7	53.0	64.7	66.2
E4 Air curing	3	27.3	23.0	18.8	17.5	23.8	17.8	19.3	19.8
	7	32.8	31.7	26.5	22.3	28.0	24.5	28.7	25.0
	28	38.5	42.5	32.8	32.3	38.3	33.7	36.5	33.7
	56	38.7	42.5	36.3	32.2	37.5	36.3	37.5	37.3
	91	43.8	41.7	38.0	31.8	42.8	36.3	38.8	37.8
	182	41.8	45.8	42.3	34.2	44.3	40.3	45.7	41.5
	364	43.2	48.0	43.5	35.5	47.0	41.7	46.3	43.0
E5 10°C water for 3 days followed by 20°C water for 24 days then air curing	3	23.8	18.3	13.8	11.2	16.0	12.7	11.7	12.8
	7	34.8	25.7	23.8	21.2	28.7	22.2	25.2	25.3
	28	50.0	53.5	44.0	41.5	47.2	44.2	46.0	44.0
	56	57.5	61.5	55.0	51.2	57.5	54.8	48.5	55.5
	91	61.7	62.3	59.7	55.3	63.7	59.8	61.7	60.0
	182	63.3	65.7	61.7	60.5	69.3	67.5	72.2	68.2
	364	63.0	65.8	61.5	62.0	67.8	67.2	70.7	69.2
E6 50°C water for 7 days followed by 27°C water for 20 days then air curing	3	31.8	31.5	32.8	34.2	40.5	38.0	41.7	35.3
	7	42.7	47.5	46.7	47.0	56.0	48.2	52.5	55.0
	28	49.8	54.5	50.8	49.2	59.8	48.5	53.0	54.0
	56	52.8	62.2	60.2	54.2	61.0	51.7	57.7	53.5
	91	55.7	62.5	57.5	57.5	64.8	53.3	57.7	56.7
	182	60.3	64.7	65.0	60.7	68.2	58.2	60.5	59.2
	364	61.7	64.5	59.5	63.5	68.7	57.8	57.8	64.7
E7 75°C water for 7 days followed by 27°C water for 20 days then air curing	3	33.8	33.7	33.3	35.5	44.5	36.5	42.7	41.8
	7	36.8	37.5	36.3	39.8	51.7	39.5	43.2	43.2
	28	38.0	39.8	39.5	44.2	50.2	41.0	45.2	44.7
	56	45.0	46.8	47.2	47.5	55.7	42.7	46.3	47.7
	91	48.2	49.2	48.0	50.3	62.2	45.0	48.7	47.8
	182	51.2	54.0	53.0	54.0	62.3	48.5	49.0	48.2
	364	50.7	54.3	53.2	55.7	60.8	51.0	51.0	50.0

Notes:
(1) The details of the concrete mixes and the curing environment are given in Table 5, 6 and 7 respectively. For easy reference, the proportions of GGBS/PC/SF in percentage are also given.
(2) The mean compressive strengths in this Table are taken from Tables 8 to 37 of this Report and are in units of MPa.

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Table 40 - Mean Compressive Strength for Grade 45 Mixes (CRC)

Curing Environment	Age (days)	Grade 45 Concrete							
		M2	M10/45C	M11/45C	M12/45C	M13/45C	M14/45C	M15/45C	M16/45C
		0/100/0	30/70/0	50/50/0	70/30/0	80/20/0	47.5/47.5/5	67.5/27.5/5	75/20/5
E1 27°C water for 27 days then air curing	28	58.7	60.8	63.3	71.0	69.2	74.5	71.7	71.8
	56	69.5	72.0	73.2	79.5	78.0	83.3	85.3	83.3
	91	72.2	74.8	73.5	89.7	86.2	87.3	90.0	87.0
	182	74.2	72.5	75.5	89.2	81.3	87.8	90.3	88.3
	364	72.5	60.3	77.7	90.0	83.7	90.8	91.7	90.3
E2 27°C water for 7 days then air curing	7	47.3	43.2	40.5	46.7	43.3	49.3	48.5	45.5
	28	63.8	60.2	60.7	66.0	63.5	70.8	70.3	64.3
	56	62.0	64.8	64.3	72.7	69.0	73.2	74.2	72.5
	91	61.8	70.0	66.3	77.2	77.7	76.2	77.7	77.5
	182	64.8	65.5	67.8	80.3	77.0	81.2	80.5	79.7
	364	64.8	56.0	72.0	80.5	77.2	83.0	80.0	80.7
E3 27°C water for 3 days then air curing	3	36.0	28.0	25.2	29.3	29.5	31.0	33.0	34.0
	7	47.8	42.7	43.8	46.5	50.3	51.5	47.7	49.5
	28	59.5	55.5	54.2	63.8	64.5	67.0	65.5	62.3
	56	61.7	60.3	59.7	71.2	65.2	64.7	68.0	66.5
	91	62.5	62.3	60.5	76.8	72.8	70.2	74.2	73.0
	182	61.5	61.5	64.2	78.3	73.7	76.8	75.5	72.7
	364	59.3	63.5	66.8	82.7	71.0	77.8	77.0	74.3
E4 Air curing	3	32.2	27.3	25.7	28.2	28.5	30.0	32.0	33.0
	7	38.5	34.2	32.2	34.7	31.3	37.5	37.5	33.8
	28	47.0	40.5	42.0	43.2	40.5	50.3	47.8	43.5
	56	46.0	47.0	44.5	46.5	41.7	49.0	47.8	46.7
	91	50.8	48.8	51.0	51.5	48.2	52.8	50.5	51.5
	182	51.3	49.0	50.2	53.7	49.7	58.5	52.2	55.0
	364	51.5	49.0	52.2	54.7	49.2	59.5	52.5	54.3
E5 10°C water for 3 days followed by 20°C water for 24 days then air curing	3	28.5	22.3	17.5	18.2	18.8	21.0	18.7	24.3
	7	44.3	36.8	31.0	36.2	37.0	38.0	36.0	38.3
	28	60.0	58.0	55.3	58.3	53.7	62.2	60.2	59.2
	56	68.8	69.3	67.7	71.7	68.8	75.7	69.7	71.5
	91	68.3	74.7	73.5	80.7	78.0	81.5	83.2	78.0
	182	73.2	72.0	75.8	85.5	81.2	90.0	91.7	87.5
	364	73.7	73.3	76.2	84.2	81.3	87.8	90.0	87.3
E6 50°C water for 7 days followed by 27°C water for 20 days then air curing	3	41.0	42.5	47.0	56.8	54.7	65.5	64.3	55.2
	7	50.7	52.8	51.8	68.3	66.3	72.3	73.5	69.5
	28	59.0	59.0	66.5	71.7	66.0	73.3	70.7	72.2
	56	62.0	68.8	68.3	78.2	67.7	74.8	75.3	73.0
	91	68.8	73.5	78.0	79.7	72.3	79.5	76.0	74.3
	182	72.2	70.8	72.2	82.5	76.0	78.7	77.7	79.5
	364	73.7	73.2	76.0	80.0	75.5	79.0	76.7	77.8
E7 75°C water for 7 days followed by 27°C water for 20 days then air curing	3	42.5	41.2	45.7	59.5	55.8	58.3	59.8	60.2
	7	44.5	45.8	50.3	61.7	60.8	62.2	61.0	60.8
	28	47.7	47.8	55.2	64.8	63.8	64.2	60.8	62.5
	56	52.2	56.2	62.5	67.7	65.0	63.5	60.5	64.0
	91	57.7	61.0	65.5	72.0	66.8	64.8	63.7	65.8
	182	58.3	63.3	62.0	75.3	70.0	68.8	67.8	66.7
	364	58.2	60.5	65.3	75.7	71.0	66.7	65.0	67.2

Notes:
(1) The details of the concrete mixes and the curing environment are given in Table 5, 6 and 7 respectively. For easy reference, the proportions of GGBS/PC/SF in percentage are also given.
(2) The mean compressive strengths in this Table are taken from Tables 8 to 37 of this Report and are in units of MPa.

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Table 41 - Mean Compressive Strength for Grade 45 Mixes (SG)

Curing Environment	Age (days)	Grade 45 Concrete							
		M2	M10/45S	M11/45S	M12/45S	M13/45S	M14/45S	M15/45S	M16/45S
		0/100/0	30/70/0	50/50/0	70/30/0	80/20/0	47.5/47.5/5	67.5/27.5/5	75/20/5
E1 27°C water for 27 days then air curing	28	58.7	66.0	60.5	61.2	68.5	66.0	61.0	68.8
	56	69.5	74.3	68.0	73.3	79.0	75.7	71.8	80.5
	91	72.2	78.3	73.2	75.0	81.2	80.5	73.0	81.5
	182	74.2	78.0	79.2	79.8	81.8	81.2	78.2	87.5
	364	72.5	80.0	76.0	77.5	84.7	83.2	83.0	86.3
E2 27°C water for 7 days then air curing	7	47.3	43.5	37.7	37.3	42.7	39.2	38.7	43.8
	28	63.8	64.5	56.8	56.5	63.2	59.3	56.3	61.8
	56	62.0	66.7	59.5	61.2	68.2	63.2	61.8	70.2
	91	61.8	70.0	62.7	63.0	71.2	64.7	62.7	71.2
	182	64.8	73.5	68.5	68.0	77.2	71.2	68.3	77.3
	364	64.8	75.0	69.3	69.3	76.8	74.8	69.8	79.7
E3 27°C water for 3 days then air curing	3	36.0	29.8	22.8	22.7	31.2	24.5	20.8	29.3
	7	47.8	45.3	41.5	36.7	41.0	45.2	36.8	44.0
	28	59.5	60.8	51.8	52.7	58.5	54.0	48.8	55.8
	56	61.7	60.7	56.0	59.3	59.5	59.5	55.8	64.8
	91	62.5	65.0	56.0	57.3	64.7	58.5	55.8	65.7
	182	61.5	67.3	65.0	63.8	72.3	66.0	63.3	73.2
	364	59.3	68.5	63.7	65.8	74.5	67.3	63.0	74.5
E4 Air curing	3	32.2	27.8	23.8	20.7	28.8	24.5	21.0	24.7
	7	38.5	35.7	30.0	28.3	31.3	32.8	29.8	32.3
	28	47.0	49.8	41.0	41.0	44.0	43.2	38.5	43.2
	56	46.0	48.7	41.2	44.2	46.8	46.0	38.2	47.0
	91	50.8	50.5	44.2	40.7	48.3	47.5	43.3	48.7
	182	51.3	54.7	50.5	44.3	51.2	52.5	45.0	51.5
	364	51.5	55.8	52.0	46.5	53.7	53.8	46.5	52.5
E5 10°C water for 3 days followed by 20°C water for 24 days then air curing	3	28.5	22.2	17.0	13.7	20.3	17.0	12.5	15.8
	7	44.3	30.7	27.7	26.8	32.7	30.7	26.5	31.7
	28	60.0	62.2	51.3	49.7	54.0	54.2	48.0	52.7
	56	68.8	69.0	62.0	60.7	67.0	65.0	59.0	67.2
	91	68.3	73.8	65.8	65.0	74.0	70.0	69.3	73.3
	182	73.2	76.0	71.8	70.2	78.8	80.2	75.0	76.5
	364	73.7	77.3	70.0	72.7	80.7	79.3	75.3	80.8
E6 50°C water for 7 days followed by 27°C water for 20 days then air curing	3	41.0	39.5	41.8	44.8	46.8	50.5	46.0	45.2
	7	50.7	55.2	56.0	62.7	66.5	61.0	58.0	64.5
	28	59.0	63.2	59.0	62.5	67.8	63.7	59.2	67.2
	56	62.0	71.0	67.8	66.8	71.0	66.7	65.5	72.0
	91	68.8	74.2	67.8	70.3	76.8	68.5	64.5	73.2
	182	72.2	74.0	71.7	71.7	77.0	71.0	66.5	76.0
	364	73.7	78.0	71.8	73.8	78.8	74.3	67.0	74.5
E7 75°C water for 7 days followed by 27°C water for 20 days then air curing	3	42.5	42.8	40.0	48.3	53.8	50.3	46.5	55.2
	7	44.5	47.2	46.2	54.0	63.5	54.2	48.2	56.3
	28	47.7	51.2	51.0	56.0	64.2	54.3	47.8	57.8
	56	52.2	58.0	57.8	62.0	68.0	55.8	49.5	59.8
	91	57.7	63.7	61.2	62.5	68.5	58.7	53.8	60.7
	182	58.3	60.3	63.2	63.8	69.7	62.0	53.5	62.3
	364	58.2	63.5	65.5	68.5	70.5	62.8	55.5	60.3

Notes:
(1) The details of the concrete mixes and the curing environment are given in Table 5, 6 and 7 respectively. For easy reference, the proportions of GGBS/PC/SF in percentage are also given.
(2) The mean compressive strengths in this Table are taken from Tables 8 to 37 of this Report and are in units of MPa.

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Table 42 - Summary of Peak Temperature at the Centre of Concrete Panel

Grade 35 Concrete						
Mix I.D. No.	Mix proportion (GGBS/PC/SF)	Total cementitious content	Peak Temp. (°C)	Ambient Temp. (°C)	Peak Temp. above ambient (°C)	Temp. raised / 100kg cementitious material
M1	0/100/0	390	80.5	31.0	49.5	12.5
M3/35C	30/70/0	415	87.0	31.5	55.5	13.5
M4/35C	50/50/0	370	83.5	30.5	53.0	14.5
M5/35C	70/30/0	390	82.0	29.0	53.0	13.5
M6/35C	80/20/0	480	82.5	29.5	53.0	11.0
M7/35C	47.5/47.5/5	400	78.0	28.5	49.5	12.5
M8/35C	67.5/27.5/5	400	75.0	30.0	45.0	11.5
M9/35C	75/20/5	435	71.5	31.0	40.5	9.5
M3/35S	30/70/0	415	83.5	28.0	55.5	13.5
M4/35S	50/50/0	370	83.0	32.5	50.5	13.5
M5/35S	70/30/0	390	82.0	30.0	52.0	13.5
M6/35S	80/20/0	480	83.0	32.5	50.5	10.5
M7/35S	47.5/47.5/5	400	80.0	32.0	48.0	12.0
M8/35S	67.5/27.5/5	400	73.5	28.5	45.0	11.5
M9/35S	75/20/5	435	74.5	32.5	42.0	9.5

Grade 45 Concrete						
Mix I.D. No.	Mix proportion (GGBS/PC/SF)	Total cementitious content	Peak Temp. (°C)	Ambient Temp. (°C)	Peak Temp. above ambient (°C)	Temp. raised / 100kg cementitious material
M2	0/100/0	445	86.0	33.0	53.0	12.0
M10/45C	30/70/0	475	93.5	32.5	61.0	13.0
M11/45C	50/50/0	450	91.0	30.5	60.5	13.5
M12/45C	70/30/0	485	91.5	30.5	61.0	12.5
M13/45C	80/20/0	550	89.0	32.0	57.0	10.5
M14/45C	47.5/47.5/5	500	86.0	30.0	56.0	11.0
M15/45C	67.5/27.5/5	470.5	77.5	29.5	48.0	10.0
M16/45C	75/20/5	535	78.5	31.5	47.0	9.0
M10/45S	30/70/0	475	90.5	29.0	61.5	13.0
M11/45S	50/50/0	450	92.0	33.5	58.5	13.0
M12/45S	70/30/0	485	91.5	32.0	59.5	12.5
M13/45S	80/20/0	550	90.0	35.5	54.5	10.0
M14/45S	47.5/47.5/5	500	89.0	32.5	56.5	11.5
M15/45S	67.5/27.5/5	470.5	79.0	28.5	50.5	10.5
M16/45S	75/20/5	535	77.5	31.0	46.5	8.5

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Table 43 - Relative Strength Percentages for Grade 35 Mixes (CRC)

Curing Environment	Age (days)	Grade 35 Concrete							
		M1	M3/35C	M4/35C	M5/35C	M6/35C	M7/35C	M8/35C	M9/35C
		0/100/0	30/70/0	50/50/0	70/30/0	80/20/0	47.5/47.5/5	67.5/27.5/5	75/20/5
E1 27°C water for 27 days then air curing	28	100%	100%	100%	100%	100%	100%	100%	100%
	56	117%	111%	118%	118%	117%	115%	116%	116%
	91	127%	116%	120%	125%	132%	121%	124%	123%
	182	128%	117%	119%	126%	129%	128%	131%	128%
	364	126%	112%	120%	122%	129%	130%	128%	127%
E2 27°C water for 7 days then air curing	7	74%	71%	62%	58%	65%	64%	62%	62%
	28	103%	101%	94%	91%	99%	99%	97%	89%
	56	105%	108%	103%	97%	105%	103%	101%	100%
	91	114%	111%	101%	104%	117%	109%	109%	108%
	182	115%	106%	108%	110%	118%	118%	113%	116%
	364	111%	101%	108%	110%	118%	119%	113%	121%
E3 27°C water for 3 days then air curing	3	59%	46%	38%	36%	41%	37%	37%	42%
	7	80%	70%	68%	61%	73%	66%	64%	65%
	28	99%	93%	87%	85%	94%	87%	88%	86%
	56	104%	100%	90%	96%	98%	90%	93%	92%
	91	114%	99%	93%	103%	108%	98%	100%	100%
	182	108%	101%	100%	111%	109%	104%	104%	105%
	364	110%	92%	104%	112%	107%	108%	111%	109%
E4 Air curing	3	56%	48%	39%	35%	40%	38%	37%	39%
	7	67%	58%	52%	46%	50%	48%	48%	46%
	28	79%	72%	67%	56%	59%	63%	64%	54%
	56	79%	79%	72%	64%	61%	67%	60%	59%
	91	89%	79%	75%	68%	72%	76%	64%	64%
	182	85%	85%	83%	73%	75%	79%	66%	71%
	364	88%	83%	86%	75%	75%	80%	67%	73%
E5 10°C water for 3 days followed by 20°C water for 24 days then air curing	3	49%	36%	29%	24%	28%	26%	21%	28%
	7	71%	59%	47%	47%	52%	48%	43%	52%
	28	102%	98%	91%	82%	84%	87%	83%	81%
	56	117%	112%	109%	103%	98%	105%	101%	100%
	91	126%	117%	117%	114%	115%	117%	113%	113%
	182	129%	120%	114%	123%	106%	128%	128%	124%
	364	129%	109%	120%	124%	122%	129%	128%	130%
E6 50°C water for 7 days followed by 27°C water for 20 days then air curing	3	65%	68%	72%	78%	76%	79%	78%	76%
	7	87%	91%	96%	93%	94%	93%	96%	97%
	28	102%	99%	101%	97%	98%	97%	95%	95%
	56	108%	110%	114%	105%	99%	101%	102%	105%
	91	114%	117%	121%	115%	111%	105%	105%	104%
	182	123%	119%	117%	118%	115%	114%	111%	104%
	364	126%	103%	122%	122%	118%	114%	108%	109%
E7 75°C water for 7 days followed by 27°C water for 20 days then air curing	3	69%	66%	66%	73%	76%	76%	75%	78%
	7	75%	73%	74%	80%	88%	78%	79%	82%
	28	78%	76%	77%	83%	88%	84%	80%	78%
	56	92%	92%	92%	91%	92%	82%	84%	88%
	91	98%	95%	100%	93%	100%	83%	87%	85%
	182	104%	100%	99%	102%	121%	88%	90%	87%
	364	103%	83%	100%	106%	107%	93%	92%	90%

Note: The details of the concrete mixes and the curing environment are given in Table 5, 6 and 7 respectively. For easy reference, the proportions of GGBS/PC/SF in percentage are also given.

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Table 44 - Relative Strength Percentages for Grade 35 Mixes (SG)

Curing Environment	Age (days)	Grade 35 Concrete							
		M1	M3/35S	M4/35S	M5/35S	M6/35S	M7/35S	M8/35S	M9/35S
		0/100/0	30/70/0	50/50/0	70/30/0	80/20/0	47.5/47.5/5	67.5/27.5/5	75/20/5
E1 27°C water for 27 days then air curing	28	100%	100%	100%	100%	100%	100%	100%	100%
	56	117%	116%	112%	116%	115%	113%	113%	118%
	91	127%	120%	122%	123%	126%	118%	121%	122%
	182	128%	120%	127%	127%	128%	127%	130%	128%
	364	126%	123%	117%	127%	128%	123%	124%	131%
E2 27°C water for 7 days then air curing	7	74%	64%	58%	56%	65%	53%	63%	61%
	28	103%	99%	95%	90%	92%	87%	91%	91%
	56	105%	104%	98%	100%	101%	99%	99%	100%
	91	114%	106%	102%	101%	113%	98%	105%	107%
	182	115%	112%	108%	109%	113%	108%	115%	119%
	364	111%	112%	104%	112%	116%	110%	114%	122%
E3 27°C water for 3 days then air curing	3	59%	42%	36%	34%	41%	32%	33%	38%
	7	80%	66%	65%	55%	61%	62%	57%	62%
	28	99%	92%	89%	81%	86%	79%	77%	86%
	56	104%	99%	90%	87%	91%	89%	84%	94%
	91	114%	95%	91%	89%	101%	88%	97%	97%
	182	108%	102%	104%	100%	110%	97%	105%	114%
	364	110%	103%	107%	103%	112%	98%	112%	116%
E4 Air curing	3	56%	41%	37%	34%	41%	33%	33%	35%
	7	67%	56%	52%	44%	48%	45%	50%	44%
	28	79%	75%	64%	63%	66%	62%	63%	59%
	56	79%	75%	71%	63%	65%	67%	65%	66%
	91	89%	74%	74%	62%	74%	67%	67%	67%
	182	85%	81%	82%	67%	77%	75%	79%	73%
	364	88%	85%	85%	69%	81%	77%	80%	76%
E5 10°C water for 3 days followed by 20°C water for 24 days then air curing	3	49%	33%	27%	22%	28%	23%	20%	23%
	7	71%	46%	46%	41%	50%	41%	44%	45%
	28	102%	95%	86%	81%	82%	82%	80%	77%
	56	117%	109%	107%	100%	99%	102%	84%	98%
	91	126%	111%	116%	108%	110%	111%	107%	106%
	182	129%	117%	120%	118%	120%	125%	125%	120%
	364	129%	117%	120%	121%	117%	124%	122%	122%
E6 50°C water for 7 days followed by 27°C water for 20 days then air curing	3	65%	56%	64%	67%	70%	70%	72%	62%
	7	87%	84%	91%	92%	97%	89%	91%	97%
	28	102%	97%	99%	96%	103%	90%	92%	95%
	56	108%	110%	117%	106%	105%	96%	100%	94%
	91	114%	111%	112%	112%	112%	99%	100%	100%
	182	123%	115%	127%	118%	118%	108%	105%	104%
	364	126%	114%	116%	124%	119%	107%	100%	114%
E7 75°C water for 7 days followed by 27°C water for 20 days then air curing	3	69%	60%	65%	69%	77%	68%	74%	74%
	7	75%	67%	71%	78%	89%	73%	75%	76%
	28	78%	71%	77%	86%	87%	76%	78%	79%
	56	92%	83%	92%	93%	96%	79%	80%	84%
	91	98%	87%	94%	98%	107%	83%	84%	84%
	182	104%	96%	103%	105%	108%	90%	85%	85%
	364	103%	96%	104%	108%	105%	94%	88%	88%

Note: The details of the concrete mixes and the curing environment are given in Table 5, 6 and 7 respectively. For easy reference, the proportions of GGBS/PC/SF in percentage are also given.

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Table 45 - Relative Strength Percentages for Grade 45 Mixes (CRC)

Curing Environment	Age (days)	Grade 45 Concrete							
		M2	M10/45C	M11/45C	M12/45C	M13/45C	M14/45C	M15/45C	M16/45C
		0/100/0	30/70/0	50/50/0	70/30/0	80/20/0	47.5/47.5/5	67.5/27.5/5	75/20/5
E1 27°C water for 27 days then air curing	28	100%	100%	100%	100%	100%	100%	100%	100%
	56	118%	118%	116%	112%	113%	112%	119%	116%
	91	123%	123%	116%	126%	125%	117%	126%	121%
	182	126%	119%	119%	126%	118%	118%	126%	123%
	364	124%	99%	123%	127%	121%	122%	128%	126%
E2 27°C water for 7 days then air curing	7	81%	71%	64%	66%	63%	66%	68%	63%
	28	109%	99%	96%	93%	92%	95%	98%	90%
	56	106%	107%	102%	102%	100%	98%	103%	101%
	91	105%	115%	105%	109%	112%	102%	108%	108%
	182	111%	108%	107%	113%	111%	109%	112%	111%
	364	111%	92%	114%	113%	112%	111%	112%	112%
E3 27°C water for 3 days then air curing	3	61%	46%	40%	41%	43%	42%	46%	47%
	7	82%	70%	69%	65%	73%	69%	67%	69%
	28	101%	91%	86%	90%	93%	90%	91%	87%
	56	105%	99%	94%	100%	94%	87%	95%	93%
	91	107%	102%	96%	108%	105%	94%	103%	102%
	182	105%	101%	101%	110%	107%	103%	105%	101%
	364	101%	104%	106%	116%	103%	104%	107%	103%
E4 Air curing	3	55%	45%	41%	40%	41%	40%	45%	46%
	7	66%	56%	51%	49%	45%	50%	52%	47%
	28	80%	67%	66%	61%	59%	68%	67%	61%
	56	78%	77%	70%	65%	60%	66%	67%	65%
	91	87%	80%	81%	73%	70%	71%	70%	72%
	182	88%	81%	79%	76%	72%	79%	73%	77%
	364	88%	81%	82%	77%	71%	80%	73%	76%
E5 10°C water for 3 days followed by 20°C water for 24 days then air curing	3	49%	37%	28%	26%	27%	28%	26%	34%
	7	76%	61%	49%	51%	53%	51%	50%	53%
	28	102%	95%	87%	82%	78%	83%	84%	82%
	56	117%	114%	107%	101%	100%	102%	97%	100%
	91	116%	123%	116%	114%	113%	109%	116%	109%
	182	125%	118%	120%	120%	117%	121%	128%	122%
	364	126%	121%	120%	119%	118%	118%	126%	122%
E6 50°C water for 7 days followed by 27°C water for 20 days then air curing	3	70%	70%	74%	80%	79%	88%	90%	77%
	7	86%	87%	82%	96%	96%	97%	103%	97%
	28	101%	97%	105%	101%	95%	98%	99%	100%
	56	106%	113%	108%	110%	98%	100%	105%	102%
	91	117%	121%	123%	112%	105%	107%	106%	103%
	182	123%	116%	114%	116%	110%	106%	108%	111%
	364	126%	120%	120%	113%	109%	106%	107%	108%
E7 75°C water for 7 days followed by 27°C water for 20 days then air curing	3	72%	68%	72%	84%	81%	78%	83%	84%
	7	76%	75%	79%	87%	88%	83%	85%	85%
	28	81%	79%	87%	91%	92%	86%	85%	87%
	56	89%	92%	99%	95%	94%	85%	84%	89%
	91	98%	100%	103%	101%	97%	87%	89%	92%
	182	99%	104%	98%	106%	101%	92%	95%	93%
	364	99%	99%	103%	107%	103%	89%	91%	94%

Note: The details of the concrete mixes and the curing environment are given in Table 5, 6 and 7 respectively. For easy reference, the proportions of GGBS/PC/SF in percentage are also given.

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Table 46 - Relative Strength Percentages for Grade 45 Mixes (SG)

Curing Environment	Age (days)	Grade 45 Concrete							
		M2	M10/45S	M11/45S	M12/45S	M13/45S	M14/45S	M15/45S	M16/45S
		0/100/0	30/70/0	50/50/0	70/30/0	80/20/0	47.5/47.5/5	67.5/27.5/5	75/20/5
E1 27°C water for 27 days then air curing	28	100%	100%	100%	100%	100%	100%	100%	100%
	56	118%	113%	112%	120%	115%	115%	118%	117%
	91	123%	119%	121%	123%	118%	122%	120%	118%
	182	126%	118%	131%	131%	119%	123%	128%	127%
	364	124%	121%	126%	127%	124%	126%	136%	125%
E2 27°C water for 7 days then air curing	7	81%	66%	62%	61%	62%	59%	63%	64%
	28	109%	98%	94%	92%	92%	90%	92%	90%
	56	106%	101%	98%	100%	100%	96%	101%	102%
	91	105%	106%	104%	103%	104%	98%	103%	103%
	182	111%	111%	113%	111%	113%	108%	112%	112%
	364	111%	114%	115%	113%	112%	113%	114%	116%
E3 27°C water for 3 days then air curing	3	61%	45%	38%	37%	45%	37%	34%	43%
	7	82%	69%	69%	60%	60%	68%	60%	64%
	28	101%	92%	86%	86%	85%	82%	80%	81%
	56	105%	92%	93%	97%	87%	90%	92%	94%
	91	107%	98%	93%	94%	94%	89%	92%	95%
	182	105%	102%	107%	104%	106%	100%	104%	106%
	364	101%	104%	105%	108%	109%	102%	103%	108%
E4 Air curing	3	55%	42%	39%	34%	42%	37%	34%	36%
	7	66%	54%	50%	46%	46%	50%	49%	47%
	28	80%	76%	68%	67%	64%	65%	63%	63%
	56	78%	74%	68%	72%	68%	70%	63%	68%
	91	87%	77%	73%	66%	71%	72%	71%	71%
	182	88%	83%	83%	72%	75%	80%	74%	75%
	364	88%	85%	86%	76%	78%	82%	76%	76%
E5 10°C water for 3 days followed by 20°C water for 24 days then air curing	3	49%	34%	28%	22%	30%	26%	20%	23%
	7	76%	46%	46%	44%	48%	46%	43%	46%
	28	102%	94%	85%	81%	79%	82%	79%	77%
	56	117%	105%	102%	99%	98%	98%	97%	98%
	91	116%	112%	109%	106%	108%	106%	114%	107%
	182	125%	115%	119%	115%	115%	121%	123%	111%
	364	126%	117%	116%	119%	118%	120%	123%	117%
E6 50°C water for 7 days followed by 27°C water for 20 days then air curing	3	70%	60%	69%	73%	68%	77%	75%	66%
	7	86%	84%	93%	102%	97%	92%	95%	94%
	28	101%	96%	98%	102%	99%	96%	97%	98%
	56	106%	108%	112%	109%	104%	101%	107%	105%
	91	117%	112%	112%	115%	112%	104%	106%	106%
	182	123%	112%	118%	117%	112%	108%	109%	110%
	364	126%	118%	119%	121%	115%	113%	110%	108%
E7 75°C water for 7 days followed by 27°C water for 20 days then air curing	3	72%	65%	66%	79%	79%	76%	76%	80%
	7	76%	71%	76%	88%	93%	82%	79%	82%
	28	81%	78%	84%	92%	94%	82%	78%	84%
	56	89%	88%	96%	101%	99%	85%	81%	87%
	91	98%	96%	101%	102%	100%	89%	88%	88%
	182	99%	91%	104%	104%	102%	94%	88%	91%
	364	99%	96%	108%	112%	103%	95%	91%	88%

Note: The details of the concrete mixes and the curing environment are given in Table 5, 6 and 7 respectively. For easy reference, the proportions of GGBS/PC/SF in percentage are also given.

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Table 47 - Results of Rapid Chloride Penetration Test

			Total Charge passed (Coulombs)											
Mix No.	Source	Proportion (GGBS/PC/SF)%	28 days				56 days				91 days			
			A	B	C	Mean	A	B	C	Mean	A	B	C	Mean
M1	Control	0/100/0	> 8000 in 2 hrs				> 8000 in 2.5 hrs				> 8000 in 5.5 hrs			
M2		0/100/0	> 8000 in 2 hrs				> 8000 in 2.5 hrs				> 8000 in 5.5 hrs			
M3/35C	CRC	30/70/0	> 8000 in 3.5 hrs				8839	8841	9118	8933	8247	7840	8016	8034
M4/35C		50/50/0	6324	6546	6614	6495	4399	4960	5605	4988	5305	5782	6168	5752
M5/35C		70/30/0	2049	1935	1874	1953	1738	1826	1911	1825	1881	1929	1735	1848
M6/35C		80/20/0	1041	930	928	966	857	815	819	830	629	636	676	647
M7/35C		47.5/47.5/5	779	800	778	786	586	821	783	730	952	867	871	897
M8/35C		67.5/27.5/5	391	361	382	378	377	375	364	372	350	303	352	335
M9/35C		75/20/5	196	193	200	196	212	197	227	212	256	240	233	243
M10/45C		30/70/0	>8000 in 3.5 hrs				8363	8436	8417	8405	7268	7087	6034	6796
M11/45C		50/50/0	5606	5705	5045	5452	4264	4467	3383	4038	4765	4847	3229	4280
M12/45C		70/30/0	1797	1924	1766	1829	1345	1445	1294	1361	1200	1170	1188	1186
M13/45C		80/20/0	872	848	897	872	720	765	678	721	590	605	562	586
M14/45C		47.5/47.5/5	370	308	349	342	480	451	427	453	508	568	641	572
M15/45C		67.5/27.5/5	316	312	289	306	323	231	257	270	271	282	271	275
M16/45C		75/20/5	177	186	165	176	176	182	199	186	186	176	177	180
M3/35S	SG	30/70/0	9066	9149	9203	9139	8000	8211	8431	8214	8648	8360	8158	8389
M4/35S		50/50/0	7436	6781	5676	6631	6700	6294	6592	6529	4721	5206	5532	5153
M5/35S		70/30/0	1878	2419	2138	2145	1615	1519	1558	1564	1476	1346	1441	1421
M6/35S		80/20/0	548	661	927	712	770	717	712	733	721	658	639	673
M7/35S		47.5/47.5/5	1188	984	1116	1096	952	855	923	910	905	761	891	852
M8/35S		67.5/27.5/5	429	347	371	382	313	277	256	282	325	368	340	344
M9/35S		75/20/5	267	223	227	239	269	255	247	257	237	190	239	222
M10/45S		30/70/0	8729	8770	8781	8760	8102	7606	7014	7574	7656	7509	5881	7015
M11/45S		50/50/0	5280	6468	6263	6004	3948	4061	3855	3955	3486	3299	3200	3328
M12/45S		70/30/0	1986	1956	1768	1903	1473	1471	1450	1465	1077	1115	1163	1118
M13/45S		80/20/0	908	768	793	823	651	643	629	641	553	601	593	582
M14/45S		47.5/47.5/5	1038	914	953	968	863	921	921	902	861	800	870	844
M15/45S		67.5/27.5/5	359	392	437	396	301	320	316	312	341	320	356	339
M16/45S		75/20/5	209	194	204	202	182	182	192	185	222	200	200	207

Notes: ASTM Recommendation

Charge Passed (Coulombs)	Chloride ion Penetrability
> 4000	High
2000-4000	Moderate
1000-2000	Low
100-1000	Very Low
< 100	Negligible

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Table 48 - Effect of Sources of GGBS on Performance for Grade 35 Mixes

Curing Environment	Age (days)	Grade 35 Concrete							
		M3	M4	M5	M6	M7	M8	M9	Mean of M3 - M9
		30/70/0	50/50/0	70/30/0	80/20/0	47.5/47.5/5	67.5/27.5/5	75/20/5	
E1 27°C water for 27 days then air curing	28	0%	10%	14%	2%	6%	-8%	-4%	3%
	56	-5%	14%	16%	3%	7%	-6%	-6%	3%
	91	-3%	9%	15%	6%	8%	-6%	-3%	4%
	182	-3%	4%	13%	2%	6%	-7%	-4%	1%
	364	-10%	12%	11%	2%	11%	-5%	-8%	2%
E2 27°C water for 7 days then air curing	7	11%	15%	17%	2%	21%	-10%	-2%	8%
	28	2%	9%	15%	9%	17%	-2%	-7%	6%
	56	4%	14%	11%	5%	9%	-6%	-4%	5%
	91	5%	8%	16%	5%	14%	-5%	-3%	6%
	182	-5%	9%	15%	6%	14%	-10%	-6%	3%
	364	-11%	13%	13%	4%	12%	-10%	-5%	2%
E3 27°C water for 3 days then air curing	3	9%	15%	18%	2%	20%	2%	8%	10%
	7	6%	13%	23%	19%	12%	3%	1%	11%
	28	2%	8%	18%	10%	15%	5%	-5%	8%
	56	1%	10%	22%	8%	6%	2%	-7%	6%
	91	4%	12%	26%	8%	15%	-6%	-1%	8%
	182	-1%	6%	23%	1%	12%	-10%	-12%	3%
	364	-12%	7%	21%	-3%	14%	-9%	-12%	1%
E4 Air curing	3	14%	16%	17%	-1%	19%	3%	8%	11%
	7	4%	10%	18%	5%	11%	-12%	1%	5%
	28	-5%	14%	4%	-11%	6%	-7%	-14%	-2%
	56	5%	11%	15%	-4%	5%	-17%	-16%	0%
	91	7%	11%	21%	-1%	16%	-13%	-8%	5%
	182	4%	10%	21%	-1%	11%	-29%	-7%	1%
	364	-3%	11%	21%	-7%	9%	-31%	-8%	-1%
E5 10°C water for 3 days followed by 20°C water for 24 days then air curing	3	11%	15%	22%	2%	16%	-3%	17%	11%
	7	23%	11%	25%	7%	19%	-9%	11%	12%
	28	3%	15%	16%	4%	11%	-4%	1%	6%
	56	3%	12%	17%	0%	9%	10%	-2%	7%
	91	6%	10%	19%	6%	10%	-2%	3%	7%
	182	3%	5%	18%	-11%	8%	-6%	-1%	2%
	364	-7%	10%	16%	6%	9%	-4%	3%	5%
E6 50°C water for 7 days followed by 27°C water for 20 days then air curing	3	18%	19%	27%	10%	16%	0%	15%	15%
	7	8%	15%	15%	-1%	9%	-3%	-3%	6%
	28	3%	11%	15%	-4%	13%	-5%	-4%	4%
	56	-1%	7%	13%	-5%	11%	-6%	6%	4%
	91	5%	16%	16%	1%	11%	-3%	0%	7%
	182	3%	3%	14%	-1%	11%	-3%	-4%	3%
	364	-11%	14%	13%	1%	11%	-1%	-8%	3%
E7 75°C water for 7 days followed by 27°C water for 20 days then air curing	3	10%	11%	19%	0%	15%	-6%	2%	7%
	7	9%	13%	16%	0%	12%	-3%	4%	7%
	28	7%	10%	10%	4%	15%	-6%	-5%	5%
	56	10%	10%	13%	-3%	9%	-3%	0%	5%
	91	8%	15%	9%	-6%	5%	-5%	-3%	3%
	182	4%	6%	11%	13%	3%	-2%	-1%	5%
	364	-16%	6%	12%	3%	4%	-4%	-1%	1%

Note: The details of the concrete mixes and the curing environment are given in Table 5, 6 and 7 respectively. For easy reference, the proportions of GGBS/PC/SF in percentage are also given.

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Table 49 - Effect of Sources of GGBS on Performance for Grade 45 Mixes

Curing Environment	Age (days)	Grade 45 Concrete							
		M10	M11	M12	M13	M14	M15	M16	Mean of M10 - M16
		30/70/0	50/50/0	70/30/0	80/20/0	47.5/47.5/5	67.5/27.5/5	75/20/5	
E1 27°C water for 27 days then air curing	28	-8%	4%	14%	1%	11%	15%	4%	6%
	56	-3%	7%	8%	-1%	9%	16%	3%	6%
	91	-5%	0%	16%	6%	8%	19%	6%	7%
	182	-8%	-5%	10%	-1%	8%	13%	1%	3%
	364	-33%	2%	14%	-1%	8%	9%	4%	1%
E2 27°C water for 7 days then air curing	7	-1%	7%	20%	2%	21%	20%	4%	10%
	28	-7%	6%	14%	1%	16%	20%	4%	8%
	56	-3%	8%	16%	1%	14%	17%	3%	8%
	91	0%	6%	18%	8%	15%	19%	8%	11%
	182	-12%	-1%	15%	0%	12%	15%	3%	5%
	364	-34%	4%	14%	0%	10%	13%	1%	1%
E3 27°C water for 3 days then air curing	3	-7%	9%	23%	-6%	21%	37%	14%	13%
	7	-6%	5%	21%	19%	12%	23%	11%	12%
	28	-10%	4%	17%	9%	19%	25%	10%	11%
	56	-1%	6%	17%	9%	8%	18%	3%	8%
	91	-4%	7%	25%	11%	17%	25%	10%	13%
	182	-9%	-1%	19%	2%	14%	16%	-1%	6%
	364	-8%	5%	20%	-5%	13%	18%	0%	6%
E4 Air curing	3	-2%	7%	27%	-1%	18%	34%	25%	16%
	7	-4%	7%	18%	0%	12%	20%	4%	8%
	28	-23%	2%	5%	-9%	14%	20%	1%	1%
	56	-4%	7%	5%	-12%	6%	20%	-1%	3%
	91	-3%	13%	21%	0%	10%	14%	6%	9%
	182	-12%	-1%	17%	-3%	10%	14%	6%	5%
	364	-14%	0%	15%	-9%	10%	11%	3%	2%
E5 10°C water for 3 days followed by 20°C water for 24 days then air curing	3	1%	3%	25%	-8%	19%	33%	35%	15%
	7	17%	11%	26%	12%	19%	26%	17%	18%
	28	-7%	7%	15%	-1%	13%	20%	11%	8%
	56	0%	8%	15%	3%	14%	15%	6%	9%
	91	1%	10%	19%	5%	14%	17%	6%	10%
	182	-6%	5%	18%	3%	11%	18%	13%	9%
	364	-5%	8%	14%	1%	10%	16%	7%	7%
E6 50°C water for 7 days followed by 27°C water for 20 days then air curing	3	7%	11%	21%	14%	23%	28%	18%	18%
	7	-4%	-8%	8%	0%	16%	21%	7%	6%
	28	-7%	11%	13%	-3%	13%	16%	7%	7%
	56	-3%	1%	14%	-5%	11%	13%	1%	5%
	91	-1%	13%	12%	-6%	14%	15%	2%	7%
	182	-4%	1%	13%	-1%	10%	14%	4%	5%
	364	-7%	5%	8%	-4%	6%	13%	4%	4%
E7 75°C water for 7 days followed by 27°C water for 20 days then air curing	3	-4%	12%	19%	4%	14%	22%	8%	11%
	7	-3%	8%	12%	-4%	13%	21%	7%	8%
	28	-7%	8%	14%	-1%	15%	21%	7%	8%
	56	-3%	7%	8%	-5%	12%	18%	7%	6%
	91	-4%	7%	13%	-2%	10%	15%	8%	7%
	182	5%	-2%	15%	0%	10%	21%	7%	8%
	364	-5%	0%	9%	1%	6%	15%	10%	5%

Note: The details of the concrete mixes and the curing environment are given in Table 5, 6 and 7 respectively. For easy reference, the proportions of GGBS/PC/SF in percentage are also given.

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Figure 1 - Colour of Portland Cement and GGBS Powder

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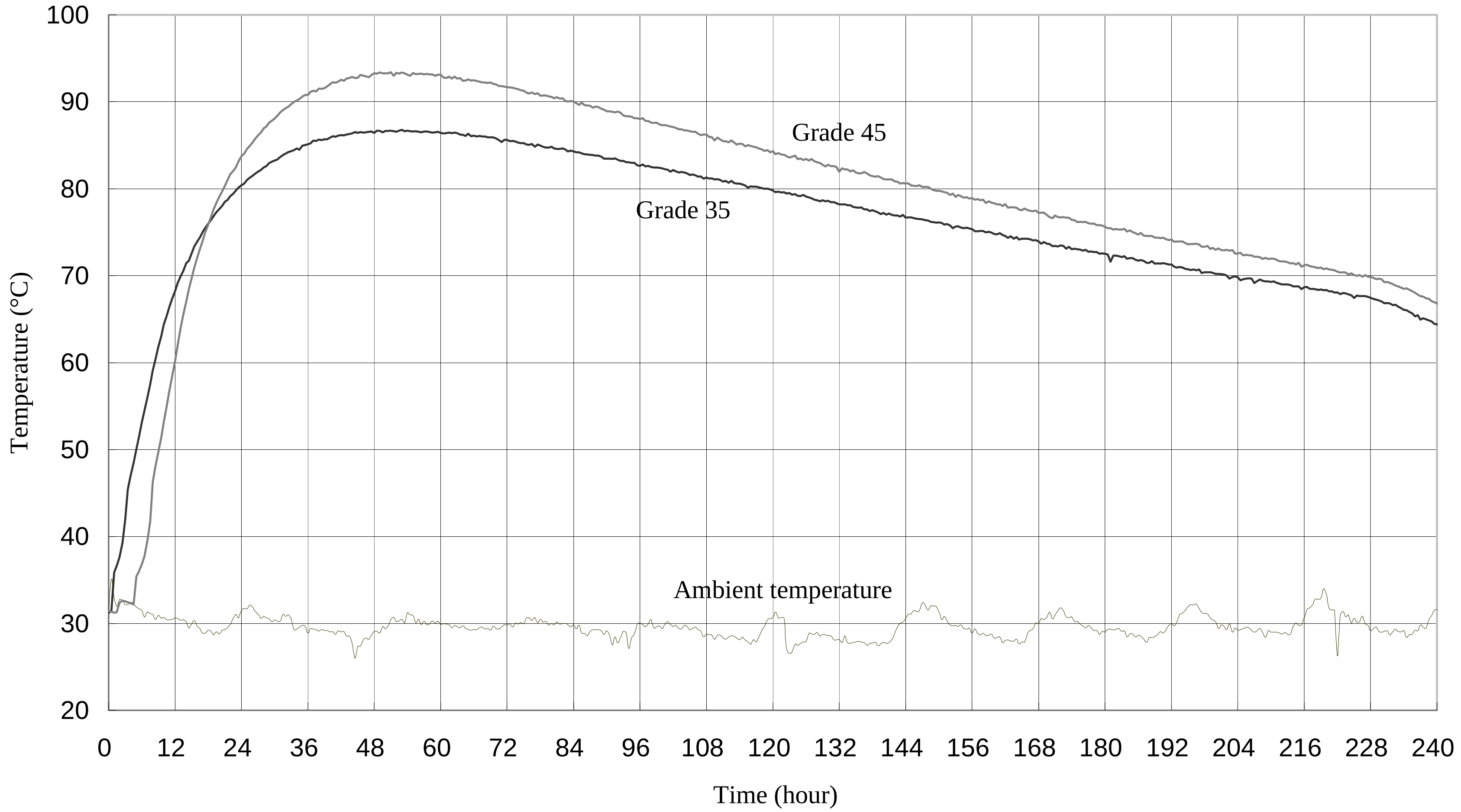

Figure 2 - Temperature Profile at Centre of Panel (Panel: M3/35C, M10/M45C)

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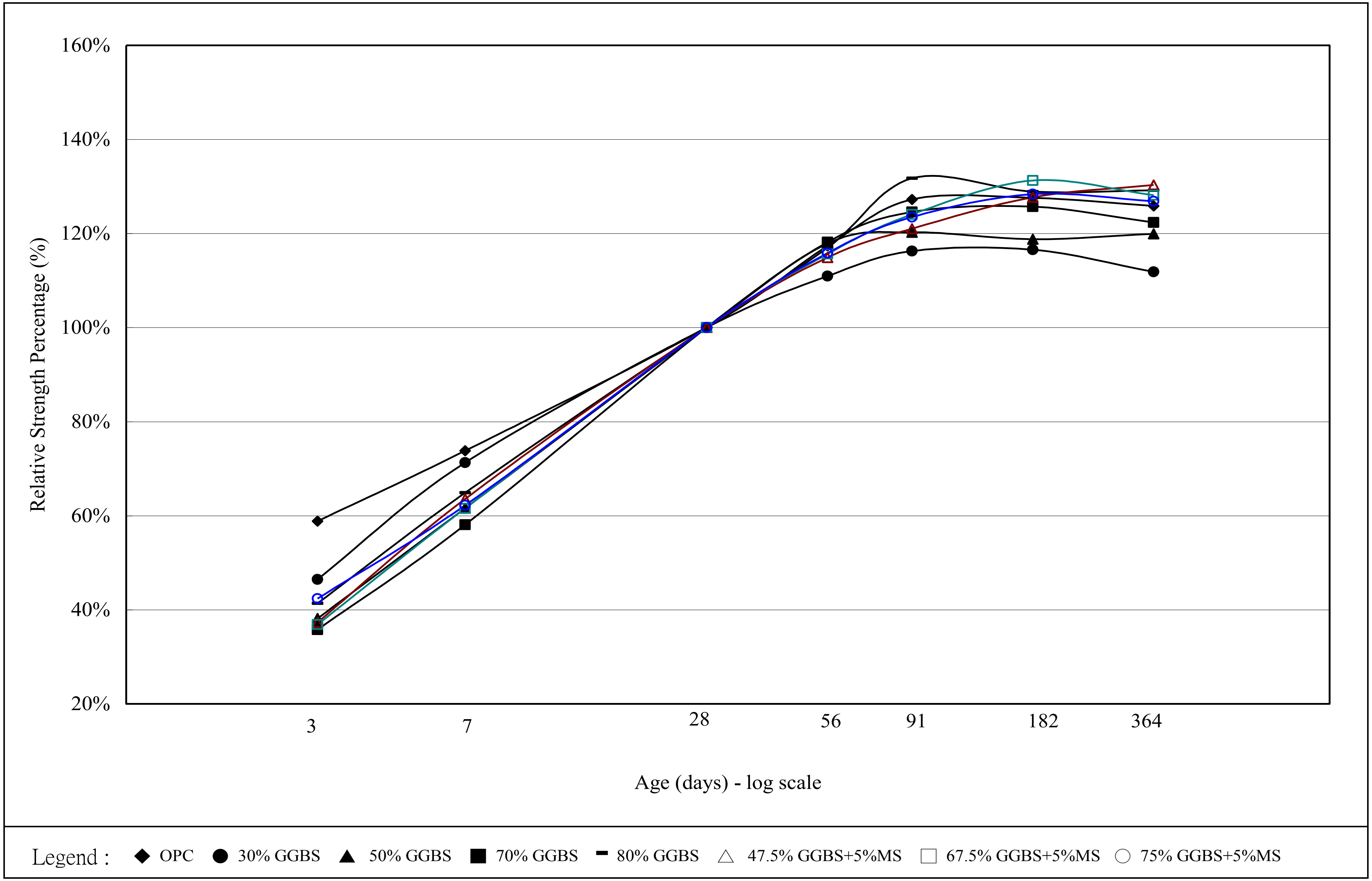

Figure 3 - Typical Strength Development of OPC and GGBS Concrete Cured under Normal Curing (CRC - Grade 35)

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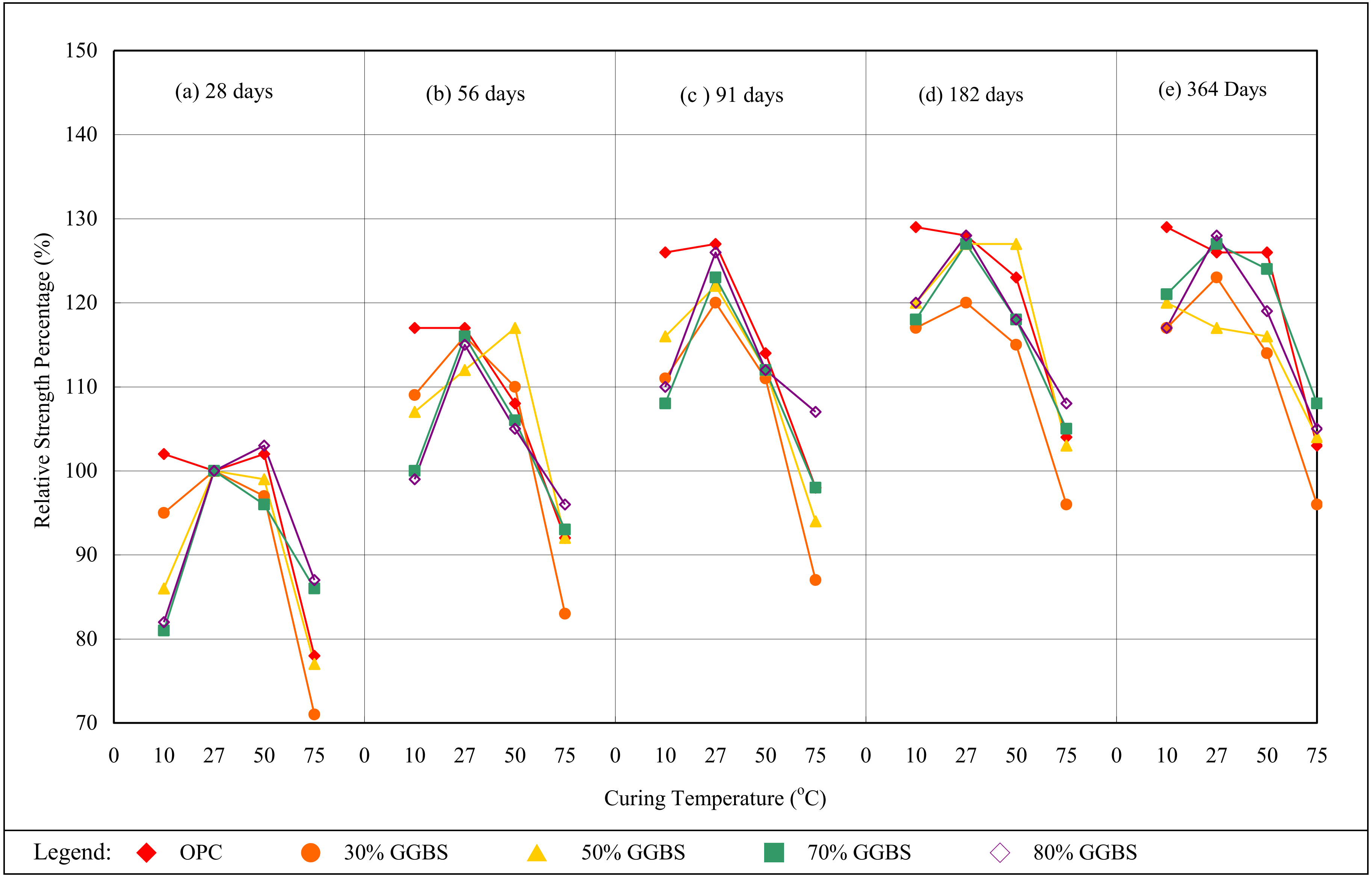

Figure 4 - Influence of Curing Temperature on the Strength Development of Grade 35 OPC and GGBS Concrete (SG)

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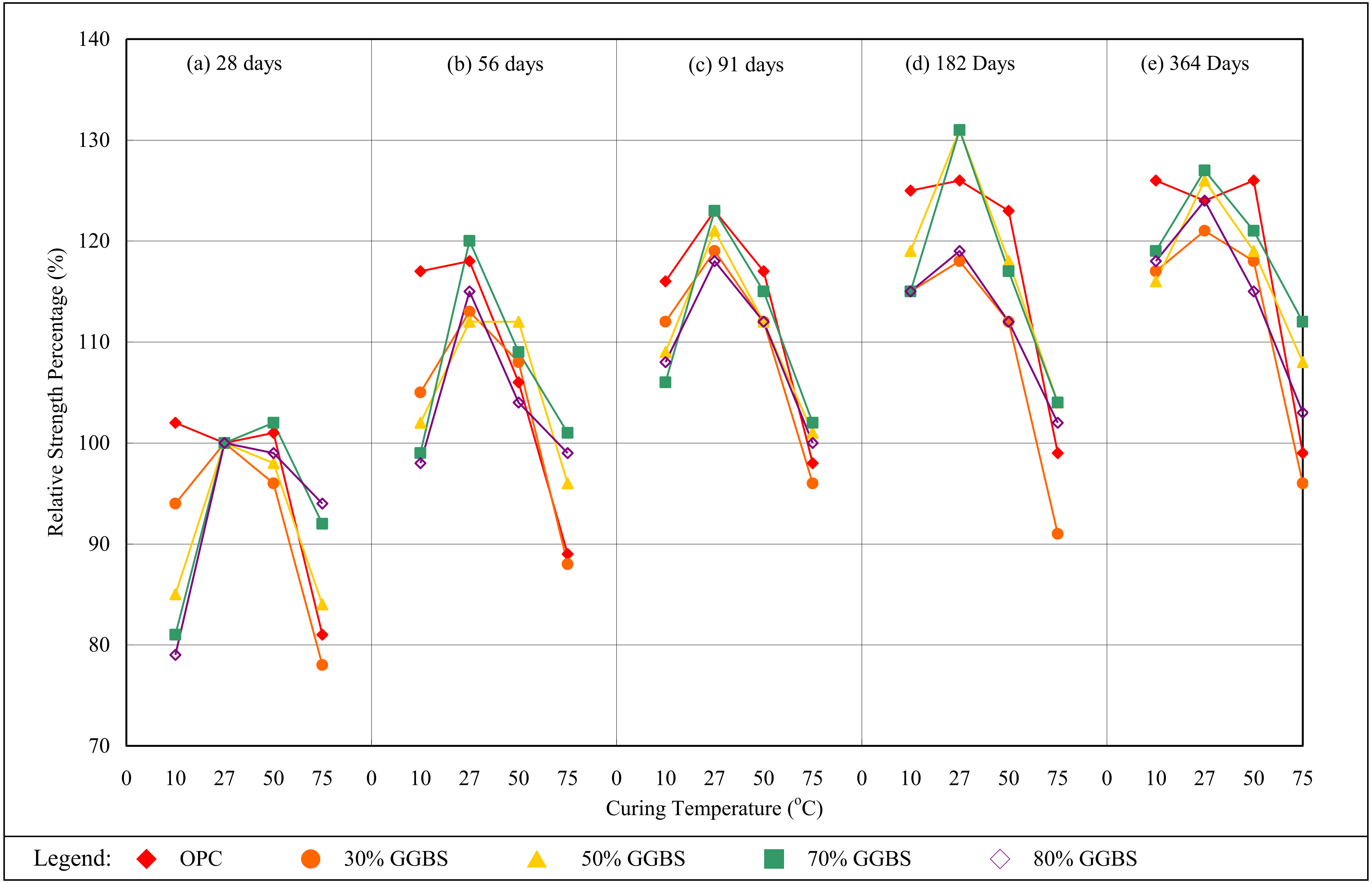

Figure 5 - Influence of Curing Temperature on the Strength Development of Grade 45 OPC and GGBS Concrete (SG)

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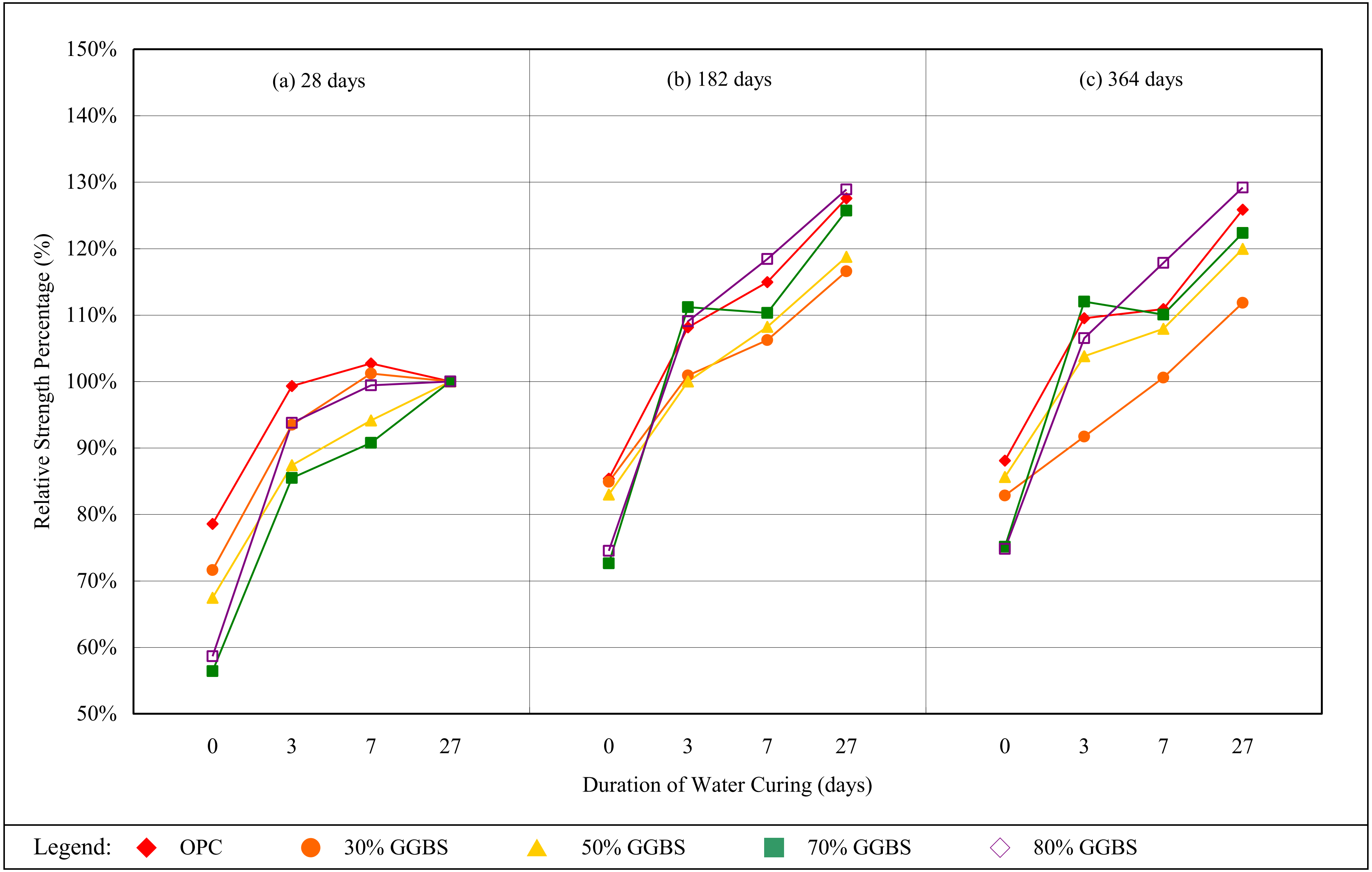

Figure 6 - Influence of Curing Duration on Strength Development (Grade 35 Mixes, SG)

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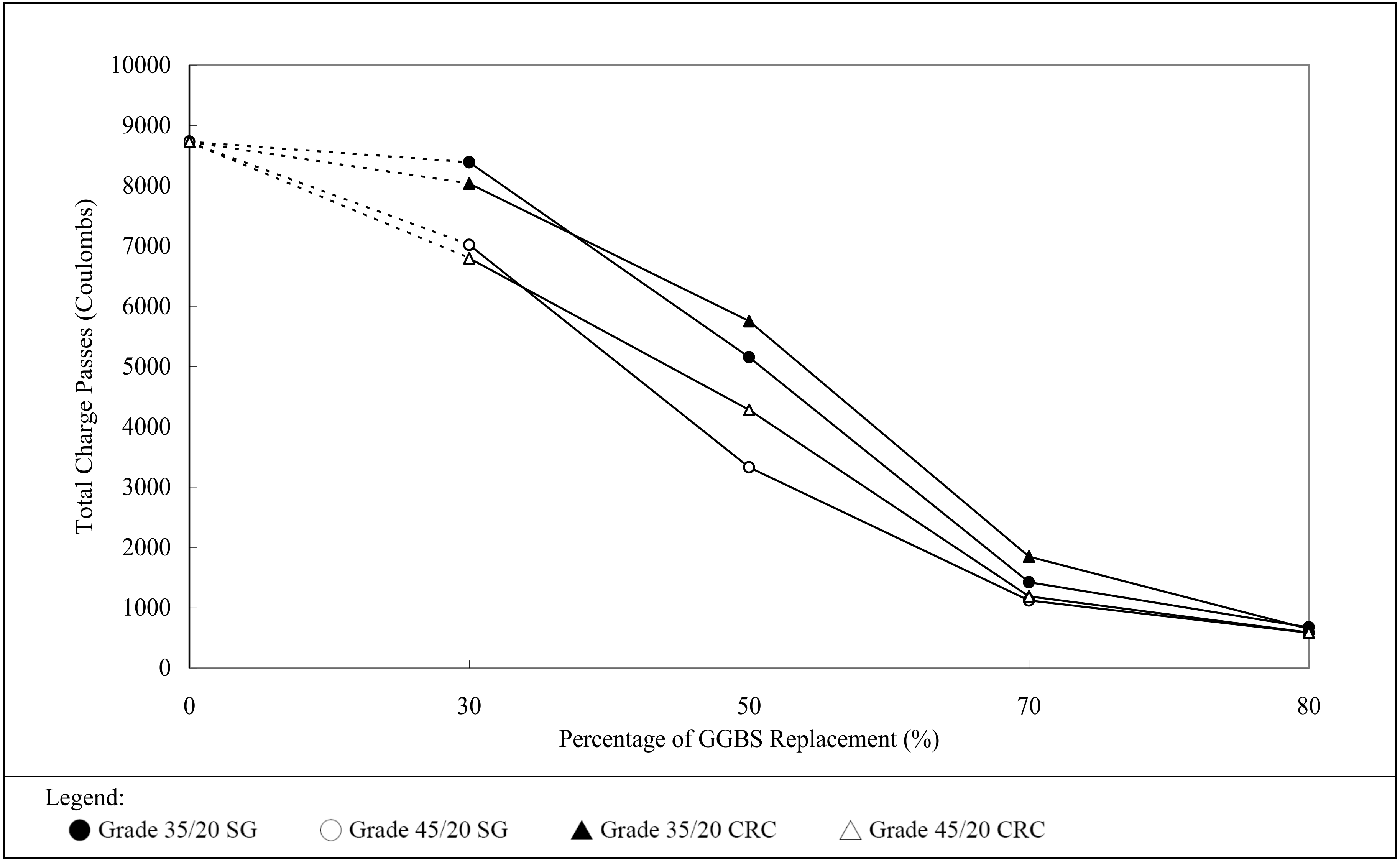

Figure 7 - Influence of GGBS Replacement on Durability at 91 days - without Silica Fume

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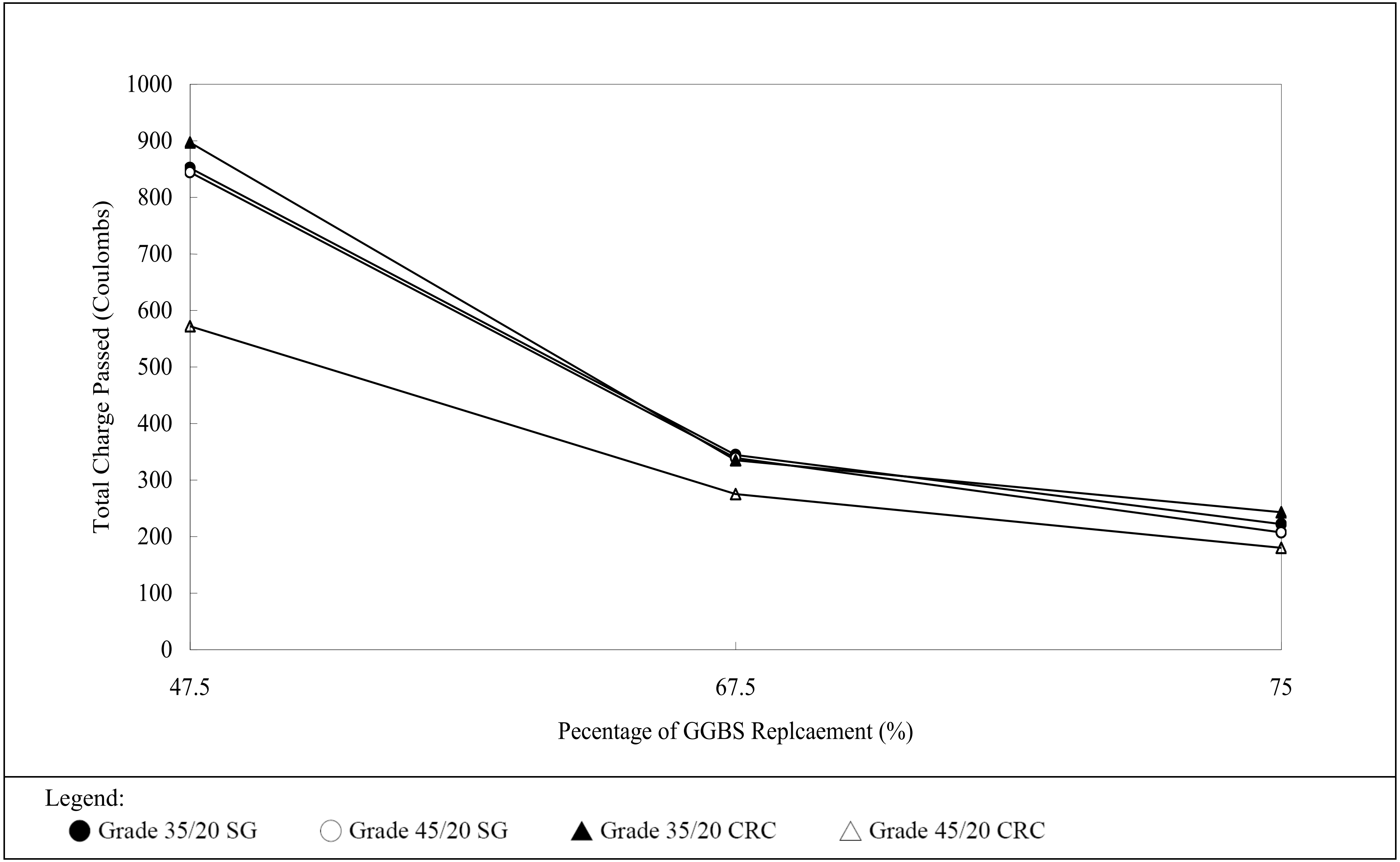

Figure 8 - Influence of GGBS Replacement on Durability at 91 days - with Silica Fume

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