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The Influence of Different European Cements on the Transport and Early-age Properties of Concrete in the Cover-zone

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THE INFLUENCE OF DIFFERENT EUROPEAN CEMENTS ON THE TRANSPORT AND EARLY-AGE PROPERTIES OF CONCRETE IN THE COVER-ZONE

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Abstract

The use of *in situ* tests for performance based specification would require demonstration of their suitability to distinguish the quality of concrete. With the introduction of new European Standards for cements, this would mean concretes produced with these new cements should be classified for their quality using the performance tests. It is generally believed that transport properties of concrete are related to their durability and hence the measurement of these properties can form the basis of performance based specifications. This paper reports data indicating that transport properties measured at 28-days for concretes manufactured with different European cements and water-binder ratios can form the basis of classifying concrete for their durability. The results also demonstrated how the different cements specified in European Standards influence the transport properties and other early-age properties.

Keywords: EN 206, concrete, cover-zone, transport properties, non-destructive testing, durability

1 INTRODUCTION

The introduction of EN 206, 2000 [1] now permits concrete to be specified in terms of its required durability depending on the exposure in which it will be located. These performance-related concrete designs now allow manufacturers to use a variety of materials to improve the performance of the concrete so that it meets the specifications set. For this, a range of cements are now available under BS EN 197, 2000 [2], which define a total of 27 different products to be used in concrete mixes. As an aid to the supplier of the concretes, BS 8500, 2006 [3] provides appropriate concrete mix recommendations in terms of the water-binder ratio (w/b), concrete strength, cement type and quantity which are deemed suitable for the exposure condition the concrete will be located in. In addition, a document by the British Cement Association [4] has provided minimum concrete mix requirements for the exposure conditions defined within EN 206, 2000 [1] based on review of published experimental results over many years. However, there appears to be little available data on performance-related specifications because there is a lack of reliable, consistent and standardised test procedure to assess if the concrete has achieved the required performance. As it is the cover-zone concrete which provides the first line of defence against the environment, it is particularly important that the performance of this zone is assessed [5].

This paper presents 28-day results of transport properties, namely the air permeability, sorptivity, chloride migration coefficient and the *in situ* chloride ion permeability coefficient using test methods developed at Queen's University Belfast over the last 20 years. The concretes used include three different cements included in BS EN 197, 2000 [2] with different w/c ratios. Results are also presented on the measured resistance across the depth of the concrete during curing using an electrode sensor embedded when cast [6-8]. Evaluating early-age properties provides an indication of potential problems and, if there are problems, adjustments or remedial measures can be initiated. The objective of the paper, therefore, is to investigate how different cements in BS EN 197, 2000 [2] affect the transport properties of concrete up to and including 28 days.

2. EXPERIMENTAL PROGRAMME

The variables used for the study are shown in Table. 1. These variables were chosen such that the samples would be suitable to resist the XS exposure conditions in EN 206, 2000 [1] as recommended in BS 8500, 2006 [3]. As shown in Table 1, three cement types, in accordance with BS EN 197, 2000 [2], and three w/c ratios were chosen; two of the cements contained different proportions of ground granulated blastfurnace slag (GGBS) as a cement replacement material. The design concrete strength used for the study was C50/55, C40/45 and C30/35 for the 0.35, 0.45 and 0.65 w/c ratios respectively. The cement contents ranged from 300 kg/m^3 to 425kg/m^3. Table 2 gives the mix proportions for the nine mixes studied. Slabs of size 230x230x100mm were used to assess the *in situ* transport properties of the hardened concretes, namely the air permeability and sorptivity, using the Autoclam Permeability System [9], and ion migration coefficient, using the Permit Ion Migration Test [10, 11]. Slabs of size 250x250x150mm were used to determine the standard migration coefficient. For this purpose, four 100 mm diameter cores were cut from these slabs at the time of testing.

Table 1 Variables used for the study

Cements	w/b ratios	Design strength (MPa)	% ggbs in the cement
CEM I	0.35 0.45 0.65	50 40 30	0
CEM II/B-S	0.35 0.45 0.65	50 40 30	35
CEM III/A	0.35 0.45 0.65	50 40 30	65

Table 2 Concrete mixes used in the testing programme

Mix designation	w/b	CEM I kg/m^3	GGBS kg/m^3	20mm kg/m^3	10mm kg/m^3	Sand kg/m^3	Plast l/m^3	Slump (mm)
CEM I	0.35	425		743	371	743	4.25	140
	0.45	360	0	753	377	753	1.80	165
	0.65	300		739	370	739	0.75	195
CEM II/B-S	0.35	276.25	148.75	736	377	736	4.25	165
	0.45	234	126	746	373	746	1.80	185
	0.65	195	105	735	368	735	0.75	195
CEM III/A	0.35	148.75	276.25	734	367	734	4.25	140
	0.45	126	234	746	373	746	1.80	125
	0.65	105	195	733	367	733	0.75	125

Note: Plast. = Plasticiser; w/b = water-binder ratio

Resistance of the concrete was also measured, for which slabs of size 250x250x150mm, with a 15mm deep dyke for ponding a 0.55M chloride solution, as shown in Figure 1, were manufactured. The ponding was carried at weekly intervals by ponding the slabs for 24 hours followed by 6 days of drying.

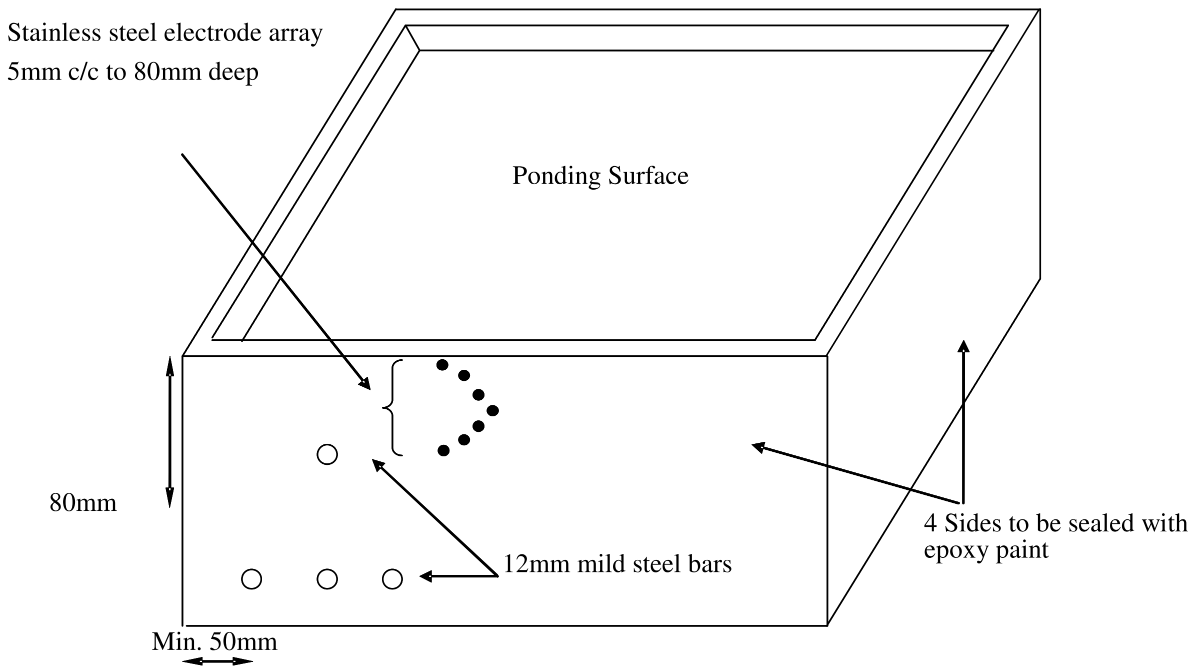


Figure 1 250x250x150mm thick slabs with 15mm deep ponding dyke used to measure resistance at 10mm intervals up to 80mm deep.

All of the slabs were cured by covering with wet hessian and sealing in polythene sheet for 7 days. At this point, they were placed in a constant temperature room at a temperature of 20 ±1 ^{0}C and relative humidity of 40 ± 2% until testing was carried out.

2.1 Autoclam air permeability

The Autoclam is an instrument used to measure air permeability, water absorption (sorptivity) and water permeability. It consists of two parts - a mechanical unit to conduct the test and an electronic controller unit to control the test and to record the data (Figure 2(a)) [9]. With an Autoclam metal ring, a 50 mm diameter test area was isolated on the clean test surface. The ring can be either clamped or glued on to the test surface. The mechanical part of the Autoclam was then connected to the test ring. The air permeability test is carried out at a 500 mBar test pressure. The pressure in the test area was raised to just above 500 mBar using a syringe. The test starts automatically when the test pressure reaches 500 mBar. When air penetrates through the concrete, the pressure in the test area decreases. The control unit monitors and records the pressure in the test area every minute for 15 minutes or until the test lasts, if it is less than 15 minutes. Time against natural logarithm of pressure for every minute is plotted. The slope of the graph is a straight line which is used as air permeability index.

2.2 Autoclam sorptivity (water absorption) test

After air permeability test, at least one hour has to lapse before commencing the sorptivity test. This is to ensure that any pressure which was built up within the concrete pores is dissipated and does not affect further test results.

The mechanical part of the Autoclam is again connected to the ring as before. The pressure for the water absorption (sorptivity) test is 20 mBar. Water is allowed in to the test area and the test is started at 20 mBar. When concrete absorbs water, the pressure in the test area decreases. More water is automatically allowed into the test area to raise the pressure back to 20 mBar. The quantity of water allowed into the test area every minute is recorded by the controller. Square root of time against cumulative volume of water is a straight line graph. The slope of this graph is used as sorptivity index.

2.3 Permit ion migration test

Permit is an *in situ* instrument (Figure 2(b)) which is used to measure the ionic transport coefficient in concrete [10, 11]. The basic principle adopted in the apparatus is similar to that of split cell migration coefficient test. Permit has an inner circular cathodic chamber in which the chloride solution is stored and an outer circular anodic chamber in which de-ionised water is stored. The base unit is designed in such a way that it will separate the chambers when fixed on to the test surface. The salt solution used has a 0.55M concentration (32.14g of NaCl in 1 litre of water). Stainless steel electrode is used in the cathodic chamber and mild steel is used in the anolite chamber (outer chamber). When the test voltage is applied (which depends on the concrete quality, typically 60V for the concretes with a w/c ratio of 0.35 and 0.45 and 30V for 0.65) between the electrodes, ionic movement takes place from the inner chamber to the outer chamber through the concrete test surface. The amount of ions reaching the anodic cell is measured with a conductivity probe, along with the current flow and temperature. When a steady state of flow is achieved, as shown by the slope of the conductivity curve, the *in situ* ion migration coefficient is calculated using a modified Nernst-Plank equation [11].

2.4 Chloride migration test

The standard chloride migration test was carried out using a split cell apparatus in accordance with the method outlined in NT Build 492 [12]. To obtain a concentration gradient for diffusion to take place, a 0.3M solution of sodium hydroxide was used in one chamber and a 10% chloride solution was used in the other chamber. The sodium hydroxide solution was prepared by mixing 12g of sodium hydroxide with 1 litre of water. The 10% chloride solution was made by adding 100g of NaCl in 900g of water. Concrete sample of 100 mm diameter and 50mm thickness cut from the core was placed between the two cells of the apparatus. This thickness of the sample was chosen to ensure that no single piece of aggregate could span or almost span from one face of the sample to the other. The samples were preconditioned by applying vacuum first for 3 hours followed by 1 hour of vacuum saturation and up to 3 days of normal saturation in a calcium hydroxide solution. Once the samples were saturated they were placed in between the cells and sealed such that the electrodes for applying the potential difference were parallel to the test surface of the specimen. In accordance with the test method outlined in NT Build 492 [12], an initial voltage of 30V was applied between the stainless steel mesh electrode (cathode), in the salt solution chamber and the mild steel mesh electrode (anode), in the sodium hydroxide chamber. The current is read from this initial voltage and using the recommendations in NT Build 492 [12], a test voltage is selected along with the test duration, which was typically 24 hours.

(a) Autoclam permeability apparatus [9]   (b) Permit chloride migration ion diffusion apparatus [10,11]

Figure 2 Autoclam and Permit apparatus

Due to the concentration gradient of salt solution in the cells and due to the voltage applied, chloride ions move from the high concentration region to the low concentration region through the concrete sample. The temperature in both the cells was measured periodically during the test to check if significant heating occurred. The flow of current in the test cells was measured with an ammeter until a steady state of chloride movement was established. The samples were then split opened and sprayed with a silver nitrite solution, which highlighted the depth of chloride penetration. This depth was measured along the sample and the chloride migration coefficient was calculated using the procedure given in NT Build 492 [12].

2.5 Covercrete electrode array sensors

The covercrete electrode array sensors consist of 10 pairs of stainless steel electrodes of 1.6mm diameter which are mounted on a small plexiglas former (Figure 3) [6-8]. Each electrode is sleeved in such a way that only a 5mm tip of the electrode is exposed. The horizontal distance between the electrodes is 5mm and the vertical distance between the two adjacent pairs of electrodes is 10mm. The electrode pairs are staggered along the vertical and horizontal planes for improved distribution of concrete around the electrodes. Thermistors are also provided in the setup for obtaining the temperature distribution through the depth. When moisture and/or chloride ions move from the surface through the concrete, the resistance of the concrete decreases, which is monitored using the array of electrodes. The data collection can also be automated to collect large amount of data at regular intervals, using which spacial variations of moisture and/or chloride around the sensor in the sample can be obtained.

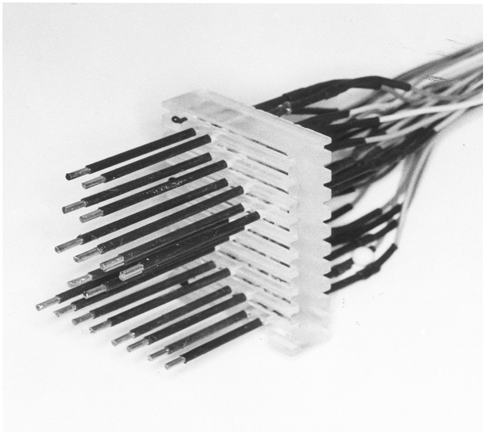


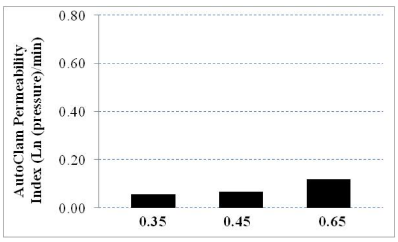
Figure 3 Electrode array electrical sensor [6-8]

3. EXPERIMENTAL RESULTS

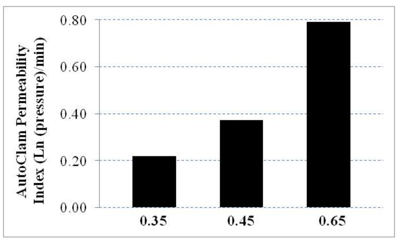
3.1 Autoclam Results

The Autoclam air permeability index (API) is shown for the three cements in Figures 4 and 5 respectively. In all cases, the slabs with the higher w/b ratios have the greatest API results, which are expected due to the higher water content and connected porosity, which is well discussed in the literature.

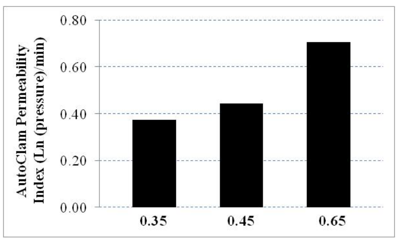
The API results for the concrete slabs with CEM I cement are lower than those in the other concrete mixes. However, it is anticipated that these differences between the three concretes will decrease over time as the supplementary cementitious materials in the other concretes continue to hydrate and decrease the ease at which air can permeate through the concrete. The Autoclam sorptivity index (ASI) results, as shown in Figure 5, follow similar trends to the API where the higher w/b ratios led to higher sorptivity values. The CEM I concretes continue to demonstrate better sorptivity than the other two cements.



(c) CEM I

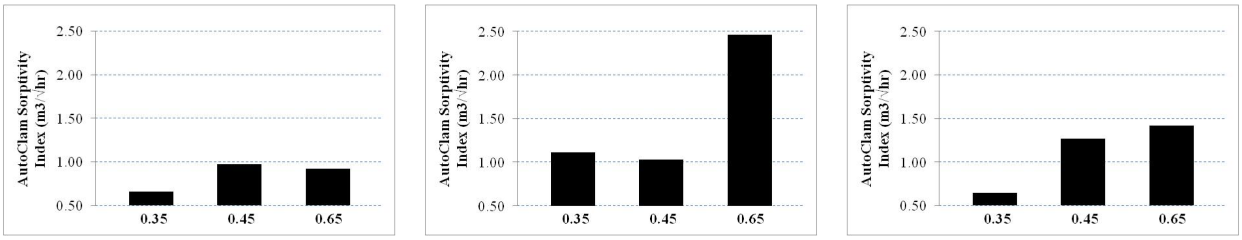


(d) CEM I + 35% Slag



(e) CEM I + 65% Slag

Figure 4 Autoclam Permeability Index for the three different cement types



CEM I CEM I + 35% Slag CEM I + 65% Slag

Figure 5 Autoclam Sorptivity Index for the three different cement types

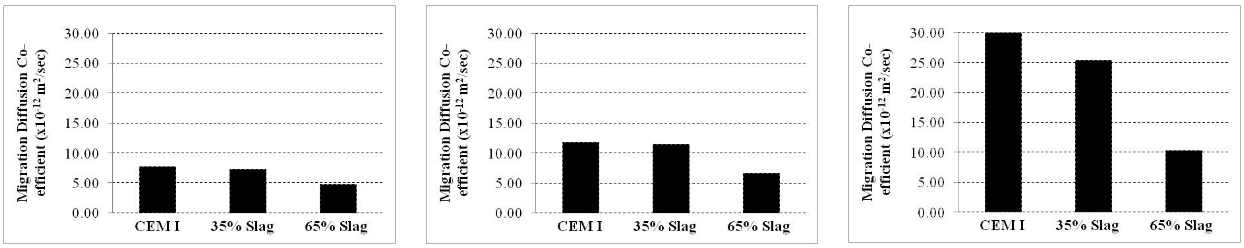
3.2 Migration Test Results

The migration coefficient based on NT Build 492 for the three cements is shown in Figure 6. As may be seen, the trends presented previously continue to be evident where the lower w/b ratio yields the lower diffusion coefficient. However, the concrete with GGBS, particularly the CEM III/A slabs appear to yield lower migration coefficients when compared to the CEM I concrete slabs (which contain no GGBS). Although the results for the three cement types for 0.35 w/b ratio appear to be similar, there are large differences between CEM III/A concrete and the other two cement types for the 0.45 and 0.65 w/b ratios.

This is a result of the chloride binding effect which is more evident in the concrete with a higher level of GGBS. Indeed, if one considers the two concretes with GGBS, the higher content does yield lower migration rates overall.

3.3 Permit Ion Migration Test Results

Figure 7 presents the Permit ion migration co-efficient for the three cements and w/b ratios. The results demonstrate similar trends as shown previously for the API and SI, where the lower w/b ratio yielded a lower migration coefficient. However, the results do indicate that the CEM III/A concretes do yield a higher migration coefficient at all w/b ratios than the CEM II/B-S concrete which have a lower slag content. One reason for this may be due to some variability in the concrete itself as the concrete used for the Permit tests was cast after that for the migration tests.

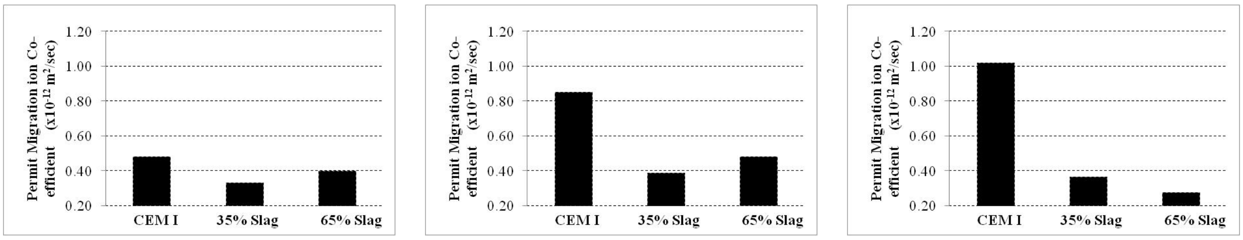


w/c = 0.35 w/c = 0.45 w/c = 0.65

Figure 6 Migration co-efficient for the three w/b ratios and cement types

3.4 Compressive Strength Results

Figure 8 presents the 100x100x100mm cube compressive strength results at 28 days for the three w/b ratios and cements used in this study. As may be seen, the CEM I concrete has the better compression strength than the other two. At 28 days of maturity, this may be expected as the strength development of concrete containing cementitious materials, such as GGBS, is slower than those without any. However, it is expected that the strength development of the concrete containing GGBS will continue for longer than the CEM I concrete. Indeed, there is little difference between the strengths between the CEM I concrete and the CEM II/B-S (35% Slag) concrete for all w/b mixes. Within the current study, the compression strength will be measured also at 56 and 90 days of age.

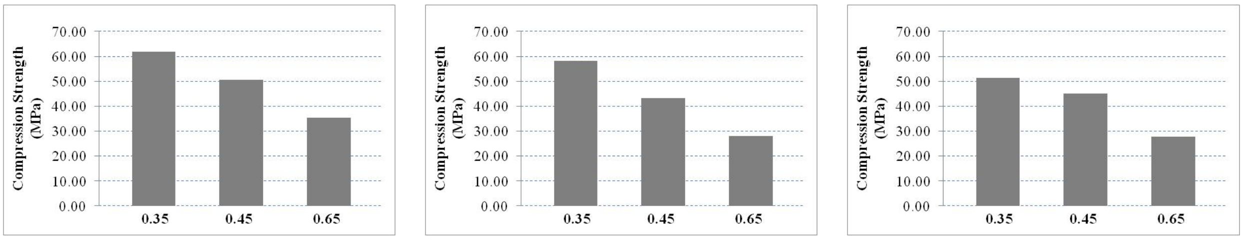


(a) w/c = 0.35 (b) w/c = 0.45 (c) w/c = 0.65

Figure 7 Permit migration ion co-efficient for the three w/b ratios and cement types

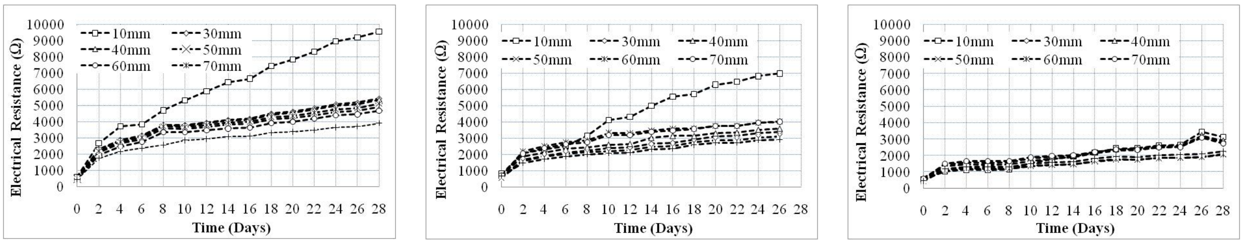
3.5 Resistance monitoring during curing

Figures 9-11 present the resistance as measured in the slabs just after casting up to 28 days using the resistivity sensors described previously. The results shown are taken over a time period from approximately 20 minutes after casting until the point at which ponding began.



CEM I CEM I + 35% Slag CEM I + 65% Slag

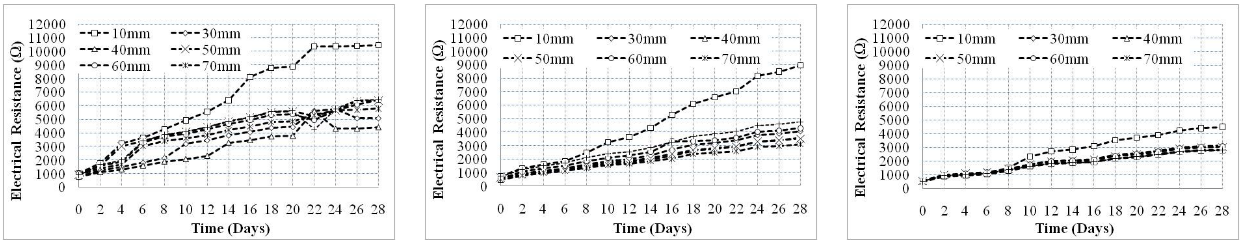
Figure 8 Compressive strength results for different cement types



CEM I – 0.35 CEM I – 0.45 CEM I – 0.65

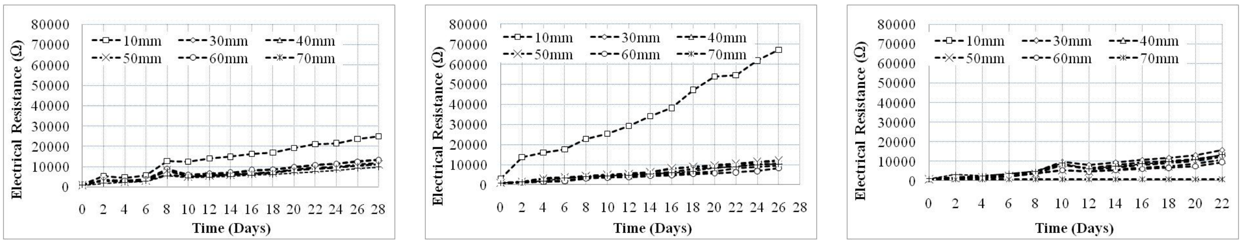
Figure 9 Resistance readings for the CEM I concrete

As stated previously, the slabs were covered with wet hessian and polythene sheet for 7-days and left to cure in a constant temperature room with temperatures and humidities of 20^0C and 40% respectively. The readings demonstrate essentially the increase in resistance through the depth of the concrete as a result of drying and hydration. The resistance measurements, particularly at 10mm, show how the lower w/b ratio (w/b = 0.35) dries out faster than those with higher w/b ratios (0.45 and 0.65). If one considers the gradient of the 10mm profile, it is clear that the rate of drying decreases with increasing w/b ratio. This finding agrees with previous work in the area of drying concrete slabs [13] which also found that drying decreased with increasing w/c ratios and is due to the reduced free water available in the concrete after hydration in lower w/b ratio concretes than in higher w/b ratios. This trend is evident for all except for the CEM III/A, w/b = 0.45, where the rate of resistance increase is much greater than the slab with w/b = 0.35.



CEM II/B-S – 0.35 CEM II/B-S – 0.45 CEM II/B-S – 0.65

Figure 10 Resistance readings for the CEM II/B-S (35% Slag) concrete



CEM III/A – 0.35 CEM III/A – 0.45 CEM III/A – 0.65

Figure 11 Resistance readings for the CEM III/A (65% Slag) concrete

4. CONCLUSIONS

The results have shown how different European cements suitable for the XS exposure condition within the new EN 206 concrete specification influence the permeability, sorptivity, migration coefficients and resistance of concretes. The results show, in general, how concretes with differing amounts of GGBS, namely CEM II/B-S and CEM III/A, improve the durability against chloride ion ingress and penetration through the cover zone. The cements have also been found to influence the rate of increase in the resistance of the concrete cover zone during curing, particularly those with GGBS.

5 ACKNOWLEDGEMENTS

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