MATERIALS TECHNOLOGY LABORATORY

Properties of Fly Ash Concrete Mixtures Made with Materials from the United Arab Emirates

A. Bilodeau, N. Bouzoubaâ, P.-C. Nkinamubanzi and R.L. Chevrier

MTL 2008-7 (TR)

March 2008

Report presented to EcoSmart Foundation Inc.

Work performed for Technology Early Action Measures (TEAM),
Funded by the Climate Change Action Fund

Properties of Fly Ash Concrete Mixtures Made with Materials from the United Arab Emirates

by

A. Bilodeau, N. Bouzoubaâ, P.-C. Nkinamubanzi and R.L. Chevrier

ABSTRACT

The EcoSmart Foundation Inc. received a contribution from the Canadian Climate Change Action Fund through the Technology Early Action Measures (TEAM) program to create a high-profile international demonstration project of the EcoSmart concrete technology in Dubai, United Arab Emirates (UAE). The Project will introduce the technology in the United Arab Emirates' extremely dynamic construction market thus providing a meaningful, world class demonstration of the technology an a model for replication that can be used in other countries. CANMET-MTL was the Delivery Agent for the Project, and also actively participated in a number of its technical activities. One of them was to design, produce and evaluate some concrete mixtures that could be used in a potential demonstration project using materials from the UAE.

Unfortunately, the demonstration project for which this testing program was designed for, was postponed, however, the information from the CANMET study could be used for other future projects in the Emirates especially the information on the effect that curing conditions relevant to the UAE environment, may have on some properties of fly ash concrete.

A total of four concrete mixtures were made. These included one control concrete without fly ash, and three mixtures incorporating different percentages of fly ash. In addition to the standard compressive strength determination under normal moist-curing conditions, the effect of curing and ambient temperature on the strength and some durability characteristics of the concrete were determined.

Fly ash concretes, having total cementitious materials content inferior to that of the control concrete, and incorporating up to 45% fly ash as partial replacement for cement, were produced and achieved compressive strengths that met the 28-day strength requirement that was specified for the potential demonstration project.

The fly ash concretes performed better than the control concrete in a number of aspects, more specifically for heat generation, resistance to chloride-ion penetration and drying shrinkage.

Although both the strength development and the resistance to chloride-ion penetration of the concretes investigated were strongly affected by the exposure to air drying at high temperature, it appears that the fly ash concretes beneficiated from some acceleration of the pozzolanic reaction due to the higher temperature during the drying period, and that this compensated, at least partly, for the lack of moist curing.

INTRODUCTION

The EcoSmart Foundation Inc. received a contribution from the Canadian Climate Change Action Fund through the Technology Early Action Measures (TEAM) program to create a high-profile international demonstration project of the EcoSmart concrete technology in Dubai, United Arab Emirates (UAE). The Project will introduce the technology in the United Arab Emirates' extremely dynamic construction market thus providing a meaningful, world class demonstration of the technology an a model for replication that can be used in other countries.

CANMET-MTL was the Delivery Agent for the Project, and also actively participated in a number of its technical activities. One of them was to design, produce and evaluate some concrete mixtures that could be used in a potential demonstration project using materials from the UAE. It was planned also to carry out a similar program in a private laboratory in Dubai. Comparing the results from the studies performed at CANMET and in Dubai, done with different aggregates and in different conditions would have been very useful for interpreting data from any future testing programs in Dubai. Unfortunately, the demonstration project for which this testing program was designed for, was postponed as well as the testing program in the Dubai private laboratory. However, the information from the CANMET study could be used for other future projects in the Emirates especially the information on the effect that curing conditions relevant to the UAE environment, may have on some properties of fly ash concrete. This report presents the information generated by the CANMET study.

SCOPE

A total of 206 kg of material (125 kg of Portland cement, 75 kg of fly ash and 6 kg of superplasticizer) were shipped from the United Arab Emirates to CANMET laboratories in Ottawa in August 2007. The materials were characterized and then used for the concrete testing program. The main objective of the program was to select the mixture with the lowest amount of Portland cement (highest proportion of fly ash) that will meet the potential demo project specifications and this, without increasing the cost of the concrete itself as well as that of the concrete construction operations. Another objective was to validate the results of a similar program that would be performed in a private laboratory in Dubai.

A total of four concrete mixtures were made. These included one control concrete without fly ash, and three mixtures incorporating different percentages of fly ash. The proportions of the mixtures were based on those proposed by the EcoSmart consultant for the potential demo project of Jetty 9. Given the very limited amount of material available for making concrete, the tests selected for the study were restricted to those that would provide information considered essential for the demo project, and with the exception of compressive strength, could not be done in the Dubai laboratory. In addition to the standard compressive strength determination under normal moist-curing conditions, the effect of curing and ambient temperature on the strength and some durability characteristics of the concrete were determined.

MATERIALS AND CONCRETE MIXTURES

Materials

Cement

The cement, which was shipped from the UAE, was an ordinary Portland cement. The physical properties and chemical analysis of the cement are given in Table 1.

Fly Ash

The fly ash, which was also shipped from the UAE , was originally from a source in India. This fly ash, commercially available in the UAE, was a low-calcium fly ash that met the requirements of a Class F fly ash according to ASTM specifications. The physical properties and chemical analysis of the fly ash are given in Table 1.

Aggregates

Both coarse and fine aggregates were from local sources near Ottawa since it would have been very costly to obtain aggregates from the UAE for this program. The coarse aggregate used was a crushed limestone and the fine aggregate was natural sand. The coarse and the fine aggregates had a specific gravity of 2.70, and water absorptions of 0.4 and 0.8%, respectively. The grading of the aggregates is given in Table 2.

Superplasticizer

A sulphonated, naphthalene formaldehyde condensate type superplasticizer, shipped from the UAE, was used in all the concrete mixtures. The superplasticizer has a solid content of 42% and a density of 1.21 kg/m^3.

Proportions of the Concrete Mixtures

A total of four concrete mixtures were made, and the proportions are summarized in Table 3. Two batches of each mixture were needed to cast all the samples required for testing. Our target compressive strength was 35 MPa at 28 days in order to meet the demo project requirements of 30 MPa. The target strength has to be higher than the specified strength to allow variations in the concrete production in the field. However, there was a possibility that the strength at 56 days instead of 28 days would be acceptable in the specification to take into account the slower strength development of the fly ash concrete as compared to that of the control.

One control concrete mixture without fly ash and mixtures incorporating 30 and 45% fly ash were made at a water-to-cementitious materials ratio (w/cm) of 0.43, which was the maximum allowable w/cm in the demo project specifications. The fourth mixture had a w/cm of 0.40 and incorporated 45% fly ash as partial replacement for cement. This mixture was made with a lower w/cm in case mixture 3 (45% fly ash, w/cm = 0.43) would not meet the 30 MPa strength requirement.

In general, for a given strength level at 28 days, and even at 56 days, the cementitious materials content of fly ash concrete would be higher than that of control concrete without fly ash. Also, the percentage of fly ash to be used in the mixture would be optimized so that all the specified requirements are met and that the cost of the fly ash mixture is lower or at least, not higher, than that of the control concrete. This is made possible when the cost of the fly ash is lower than that of Portland cement. In this particular program, the cost of fly ash in Dubai was, at that time, slightly higher than that of Portland cement. Consequently, the total amount of cementitious materials of the fly ash concrete mixtures had to be lower than that of the control concrete to avoid exceeding the cost of the latter, taking also into consideration the cost of the chemical admixtures.

It was understood that the strength at 28 and perhaps at 56 days, of the fly ash concrete mixtures, given their lower total amounts of cementitious materials, would be lower than that of the control concrete. However, this would not be an issue if the strength of the fly ash concrete met the strength and other specified requirements for the demo project. It was assumed that the compressive strength of the control concrete, designed to meet the minimum cementitious materials content (330 kg/m^3) and maximum w/cm (0.43), was probably significantly higher than that required in the specifications (30 MPa).

It should also be mentioned that the water content of 165 kg per cubic meter used for the control concrete does reflect common concrete practice in Dubai for 30 MPa concrete made with Portland cement only.

PREPARATION AND CASTING OF TEST SPECIMENS

The concrete was mixed in a laboratory counter-current pan mixer for five minutes. The properties of the fresh concrete, i.e. slump, air content and unit weight were determined immediately after the mixing according to the relevant ASTM Standards, and the results are presented in Table 4. The setting time of the concrete was determined for each mixture and the results are also given in Table 4.

For each of the concrete mixtures, fifty-two 102x203-mm cylinders were cast for determining the compressive strength, resistance to chloride-ion penetration and water absorption of the concrete, three 76x76x305-mm prisms were cast for determining the drying shrinkage, and one 152x305-mm cylinder was cast for the determination of the autogenous temperature rise of the concrete.

All the test specimens were compacted on a vibrating table. After casting, the specimens were covered and left in the casting room for 24 hours. The specimens were then demoulded and cured in a standard moist curing room at 23 ± 2°C and 100% relative humidity until specified ages.

TESTING OF SPECIMENS

The testing schedule of the concrete specimens is given in Table 5. The temperature of the concrete in semi-adiabatic conditions was monitored during the first 48 to 120 hours after mixing for three of the four mixtures. The fourth mixture (w/cm of 0.43 and 45% fly ash) could not be tested due to unavailability of equipment. The other properties determined in this program included compressive strength, resistance to chloride-ion penetration and water absorption at different ages and the drying shrinkage of concrete after 28 days of curing in lime-saturated water. Those tests were performed on concrete from all four mixtures following the relevant ASTM Standard testing methods.

The effect of the curing conditions on the compressive strength, the resistance to chloride-ion penetration and the water absorption of concrete was evaluated. For this purpose, at the ages of 1, 3 and 7 days, concrete specimens were transferred from the moist-curing room to an air-drying chamber at a temperature of 38°C. This high air-drying temperature was selected to better simulate field conditions in the Emirates where daily temperature can be very high.

After three days of moist curing, additional specimens for the determination of the resistance to chloride-ion penetration and water absorption were also air-dried at 23°C before testing whereas others were air-dried at a daily temperature cycle consisting of 8 hours at 38°C followed by 16 hours at 23°C before testing.

In the cases of compressive strength and water absorption determination, the whole specimens were exposed to the air during the air-drying period whereas for the resistance to chloride-ion penetration, only the top surface of the specimens, which is the one used for the test, was exposed to the air in order to simulate drying from one direction only.

RESULTS AND DISCUSSION

Properties of the Fresh Concrete

The properties of the fresh concrete are given in Table 4. The target slump of the concrete was from 150 to 175 mm. This was achieved for all concrete mixtures except mixture 3 for which the slump was only 100 mm. A slightly higher dosage of superplasticizer would have been required for this mixture.

The incorporation of fly ash increased the workability of the concrete as shown by the lower water and superplasticizer contents of mixtures 2 (35% fly ash) compared to those of the control. Mixture 4 also achieved a slump similar to that of the control with a similar dosage of superplasticizer but with a noticeably lower water content than that of the control. The slightly lower water and superplasticizer contents of mixture 3, as compared to mixture2 partly explain the lower slump value of the former mixture. However, given the significant difference in slump between these two mixtures, it is possible that there is an optimum percentage of fly ash replacement for workability and that 45%, is beyond that optimum value. More data would be needed to confirm this.

The air content of the mixtures ranged from 1.2 to 2.0%, which are normal values for non-air entrained concrete. The unit weight of the concrete mixtures ranged from 2390 to 2430 kg/m^3.

Setting Time

The final setting time of mixtures 1, 2 and 3 was very similar, ranging from 9 hours and 20 minutes to 9 hours and 40 minutes (Table 4). There were small differences for the initial setting time of the same three mixtures with values of 6 hours and 50 minutes for mixture 3, 7 hours and 20 minutes for mixture 2, and 7 hours and 45 minutes for mixture 1. Generally speaking, the reverse trend would have been expected, i.e. longer setting time with higher percentages of fly ash replacement. In this case, the explanation for the slightly longer setting time of the control concrete could be its higher dosage of superplasticizer, which is suspected to contain some set retarding admixture.

The setting times of mixture 4 were significantly longer than those of the other mixtures of this study; approximately 3 hours more for both the initial and final setting times. The explanation for this would be the higher dosage of superplasticizer of mixture 4 combined to the high level of cement replacement (45%). Again this is an indication of the possible presence of set retarding admixture in the superplasticizer.

Autogenous Temperature Rise

The temperature of the concrete in semi-adiabatic conditions during the first few days after mixing is illustrated in Figure 1 for the mixture 1, 2 and 4. It shows that the control mixture generated significantly more heat, and at a much faster rate, than both fly ash mixtures. The maximum temperature rise of the control concrete was 23.3°C, as compared to 14.0°C for the mixture 2 (35% fly ash; w/cm = 0.43) and only 11.1°C for the mixture 4 (45% fly ash; w/cm = 0.40).

The significantly lower heat generation of fly ash concrete, as demonstrated in this study, is a significant advantage of that type of concrete for reducing thermal stress and the risk of thermal cracking in massive concrete elements.

Compressive Strength

Standard Moist Curing Conditions

Three mixtures, 1, 2 and 4, achieved the minimum required strength of 30 MPa at 28 days (Table 6). Mixture 3 failed to meet that requirement with a 28-day compressive strength of 26.1 MPa. As expected, the control concrete has shown the highest compressive strength at 28 days with a value of 47.2 MPa. As mentioned earlier, it was expected that a control concrete meeting the project specifications for minimum cement content and maximum w/cm would be over-designed for the strength requirement of this project.

The mixture 2 (35% fly ash; w/cm = 0.43) easily met the minimum strength requirement with a 28-day compressive strength of 35.7, which is also slightly higher than the target strength of 35 MPa. The strength of mixture 4 (45% fly ash; w/cm = 0.40) exceeds the requirement with a value of 31.7 but is lower than the target strength.

At the age of 56 days, all four mixtures met the minimum strength requirements but the mixture 3 still failed to meet the target strength with a test result of 33.4 MPa.

It should be noticed though that in this study, the compressive strength tests were performed on cylinders whereas the project specifications in UAE are based on tests performed on cubes, which is the standard practice in that country. It is known that in general, for specimens made from the same concrete, the strength of cubes will be higher than that of cylinders. However, there is no simple relation between the strength of the specimens of the two shapes (1). Generally speaking, for the level of strength at 28 and 56 days of this study, a value of compressive strength determined on cylinders approximately 10% lower than that determined on cubes would be expected (1). Considering this, all four mixtures in this program would have most probably achieved compressive strengths exceeding 35 MPa at 56 days if the test had been performed on cubes.

As expected, the compressive strength of the fly ash concretes is significantly lower than that of the control at very early ages but the strength development is faster for the fly ash concrete beyond 28 days (Figure 2). At 56 days, the compressive strength of the mixture 2 (35% fly ash; w/cm = 0.43) is almost equal to that of the control. Increasing the fly ash proportion from 35 to 45% without reducing the w/cm (mixtures 2 and 3) resulted in a significant reduction of the compressive strength. The reduction of the w/cm from 0.43 to 0.40 (mixtures 3 and 4) contributed to increase considerably the compressive strength except at one day. The low one-day strength of the mixture 4 is possibly due to the potential retarding effect of the superplasticizer as noticed for the setting time test results.

Effect of the Curing Regime

For all concretes investigated in this study, when compared to the continuously moist-cured conditions, the exposure to air drying after only one day of moist curing resulted in a significant reduction of the compressive strength at both 28 and 56 days (Figures 3 to 6). In that curing regime, the mixtures incorporating 45% fly ash (mixtures 3 and 4) achieved compressive strengths of only about 23 and 25 MPa at 28 and 56 days, respectively, much lower than the strength requirement of 30 MPa specified for the demo project. It should be mentioned though that the strength requirement is based on moist-cured concrete cubes, not on air-dried specimens. It should also be mentioned that large concrete elements would be less affected on the short term than small specimens by the exposure to air-drying conditions because of the much smaller proportion of the concrete that would be affected by the lack of moisture needed for the hydration process. Consequently, comparatively to small specimens, a larger proportion of the concrete in a full-size concrete element will continue to hydrate and develop strength for a longer period after exposure to drying.

The exposure to air drying at 38°C after three days of moist curing had much less effect on the later-age strength of the concrete, especially for the three fly ash concretes for which the 28-day compressive strengths were slightly higher and, 56-day strength slightly lower than those of the continuously moist-cured specimens (Figures 3 to 6). When exposed to that curing regime, all concrete specimens showed a significant increase in strength between the ages of 3 and 7 days, possibly due to the combined effect of the dry state of the specimens and the higher temperature activating the hydration and pozzolanic reaction. Between 7 and 28 days the strength development is much slower, especially for the control concrete; the fly ash concrete perhaps, beneficiating from the higher temperature activating the pozzolanic reaction. Between the ages of 28 and 56 days the strength development of the specimens from all four mixtures was insignificant.

For all four concrete mixtures, the exposure to air drying at 38°C after seven days of moist curing resulted in 28 and 56-day compressive strengths similar to, or slightly higher than those of the specimens moist cured continuously at 23°C (Figures 3 to 6). The specimens from the four concrete mixtures exposed to that curing regime showed a noticeable increase in strength between the ages of 7 and 28 days. Again, this is possibly due to the reasons stated above. Beyond 28 days, the increase in strength of the specimens from mixture 1, 2 and 4 was minimal whereas it was a bit more significant for the specimens from mixture 3 (45% fly ash; w/cm = 0.43).

This apparent boost in strength development of air-dried specimens, which was more significant for the fly ash concrete than for the control, and the rate of strength development during the drying period, were possibly the result of the combined effect of the following factors. Firstly, the cement hydration/pozzolanic reaction process continued for some time during the drying period, contributing to increase the strength, but the process was surely affected and possibly stopped eventually, by the progressive lack of moisture. Secondly, the exposure to higher temperature may accelerate the hydration/pozzolanic reaction thus increasing the early-age strength but it may also, if it is applied at very early age, reduce slightly the later age strength as compared to concrete exposed to normal temperature (1). Finally, the test results were probably increased by the dry condition of the specimens; it is known that drying test specimens immediately before testing increases their compressive strength by about 5 to 10 percent (1).

In order to evaluate the contribution of the above factors, the results of the tests done on the moist-cured specimens have been increased arbitrarily by 10%, which is suggested in the literature as the approximate upper limit of the strength increase due to the dry condition of the specimens, and were compared in Figures 7 and 8 to the actual test results at 28 and 56 days, respectively.

It can be seen that, at 28 days, for all concretes exposed to drying at one day, the compressive strength of the dry specimens is lower than that of the moist-cured specimens and therefore, it appears that the combined effect of dry condition of the specimens and the possible acceleration of the hydration/pozzolanic reaction did not compensate for the lack of moist curing of the specimens. It is also possible that the exposure to high temperature at one day contributed somewhat to reduce the later age strength. However, when they were given three days of moist curing, the fly ash concrete specimens showed test results very similar to the theoretical (increased by 10%) test results; this was not the case for the control concrete. Since those specimens suffered from a lack of moist curing between 3 and 28 days, it appears that the fly ash concrete beneficiated significantly from the accelerating effect of the high temperature. The same trend is even more evident for the specimens moist cured for seven days before drying. In that case, the air-dried fly ash concrete specimens showed noticeably higher strengths than the theoretical specimens, reinforcing the idea that the fly ash concrete beneficiated from the accelerating effect of the high temperature.

At the age of 56 days, it appears that the acceleration of the reaction was not sufficient to fully compensate for the lack of moist curing of the specimens.

As a caveat, it must be mentioned that the above remarks about the acceleration of the hydration/pozzolanic reaction due to the high temperature are partly based on the assumption that the dry condition of the specimens would have increased their compressive strength by 10%, a value that although it was found in the literature, could be significantly different from reality in this particular case.

Resistance to Chloride-Ion Penetration

Standard Moist-Curing Conditions

The test results are presented in Table 7 and in Figures 9 and 10. The resistance to chloride-ion penetration of the concrete increased (less coulombs) with the incorporation of fly ash in the concrete as partial replacement for cement. This increased resistance to chloride-ion penetration (lower chloride-ion penetrability) of fly ash concrete, especially of concrete incorporating large proportions of fly ash has been reported by several researchers (2-5). The 28-day test result of the control concrete was 3240 coulombs compared to 2213, 1540 and 1495 coulombs for the fly ash concrete mixtures 2, 3 and 4, respectively. According to the ASTM C 1202 test method, coulomb values ranging from 2000 to 4000 correspond to moderate chloride-ion penetrability whereas values ranging from 1000 to 2000 coulombs correspond to low chloride-ion penetrability. As expected higher fly ash proportions improved the resistance to chloride-ion penetration. However, the reduction of the w/cm of the concrete (mixtures 3 and 4) had a very small effect on the results but this is based on results from only two mixtures and may not be fully representative; it is generally recognized that the reduction of the w/cm of the concrete improves significantly its resistance to chloride-ion penetration as determined by this rapid test.

The 56-day test results of the moist-cured specimens followed the same trend as those at 28 days but the coulomb values are noticeably lower, as expected. The test result of the control was 2666 coulombs, corresponding to moderate penetrability, compared to 1126, 885 and 787 coulombs for the fly ash concrete mixtures 2, 3 and 4, respectively. Therefore, according to the ASTM C 1202 test method, the chloride-ion penetrability at 56 days of the concrete incorporating 35% fly ash would be low, whereas it would be very low (less than 1000 coulombs) for both mixtures incorporating 45% fly ash.

Effect of the Curing Regime

The resistance to chloride-ion penetration of all four concretes investigated was strongly reduced at both ages by the exposure to air drying at 38°C after only one day of moist curing. The test result of the control concrete at 28 days was 5576 coulombs whereas it ranged from 4040 to 4462 coulombs for the fly ash concretes. These values correspond to high penetrability (more than 4000 coulombs) according to ASTM C 1202. There was no significant improvement at 56 days with a value of 6916 coulombs for the control and results ranging from 3433 to 4348 coulombs for the fly ash concretes. The increase in coulomb values between 28 and 56 days that was noticed for some concretes was unexpected. One possible explanation could be the presence of some microcracks, possibly due to shrinkage, that were noticed on some of the air-dried specimens.

Increasing the duration of the moist-curing period from one to three days prior to air drying improved the resistance to chloride-ion of all concretes significantly, both at 28 and 56 days. Indeed, in the case of the fly ash concrete, the 28-day resistance to chloride-ion penetration of specimens exposed to that curing regime was similar to that of the moist-cured specimens. Similarly to the compressive strength test results, it is possible that the fly ash concrete beneficiated significantly from the acceleration of the pozzolanic reaction due to the high temperature, and that this compensated, at least partly, for the lack of moist curing. The coulomb values of all the concretes were higher at 56 days than at 28 days. Again, this unexpected result could be due to the possible presence of microcracks.

All concrete mixtures demonstrated significant improvement in the resistance to chloride-ion penetration when the duration of the moist-curing period was increased from 3 to 7 days prior to the exposure to drying. At 28 days, for all concretes, the resistance to chloride-ion penetration of the specimens subjected to that curing regime was even superior to that of the moist-cured specimens. Once again, and possibly for the reason stated above, the trend was different at 56 days when two mixtures (1 and 3) showed higher coulomb values at that age than at 28 days, and also higher than their corresponding moist-cured specimens.

Comparing the results of the specimens that were moist cured for 3 days but subjected to different air drying temperatures tends to confirm the fact that the pozzolanic reaction of the fly ash concrete was accelerated by the high temperature of drying. The specimens that were air dried at 23°C showed noticeably higher chloride-ion penetrability than the specimens that were air dried at 38°C whereas those subjected to drying at a cycling temperature showed less penetrability than the former concrete specimens but slightly more than the latter.

Absorption and Volume of Permeable Voids

In general, for moist-cured specimens, the absorption and volume of permeable voids values of the fly ash concretes are slightly lower than those of the control concrete, both at 28 and 56 days (Table 8). There is one exception, mixture 3 at 56 days, but this might be due to the variability of the test method or to a non-representative sample.

Figures 11 to 14 illustrate clearly that both the absorption and the volume of permeable voids increase with the reduction of the moist curing time and that the fly ash concretes seem more affected than the control concrete, except mixture 4 that shows, in general, results similar to or slightly better than those of the control concrete. The better performance of the mixture 4 is probably due to its lower w/cm.

Drying Shrinkage

The drying shrinkage test results given in Tables 9 and 10 and illustrated in Figure 15 are partial (112 days) since the test must be performed for 64 weeks. Nevertheless, the partial results indicate that the control concrete tends to shrink more than the three fly ash concretes when exposed to drying. On the other hand, the different fly ash concretes showed similar drying shrinkage.

CONCLUSIONS

The setting time of the different concrete mixtures appeared to be somewhat affected by the dosage of superplasticizer which is suspected to contain some set-retarding admixture. Consequently, care must be taken to not overdose superplasticizer, especially for concrete incorporating higher proportions of fly ash.

The control concrete mixture generated considerably more heat, and at a much faster rate than the fly ash concrete mixtures, and this is a significant advantage for this latter type of concrete for its use in massive concrete elements where thermal stress may be an issue.

The control concrete mixture, the mixture incorporating 35% fly ash, and the mixture incorporating 45% fly ash but having a lower w/cm of 0.40, met the 28-day strength requirement of 30 MPa. At the age of 56 days, all four concrete mixtures met the 30 MPa strength requirement.

As expected, the compressive strength of the fly ash concretes was significantly lower than that of the control concrete at very early ages but the strength development of the former concrete was faster than that of the latter beyond 28 days.

Although the strength development of all four concretes was strongly affected by the lack of moist curing due to their exposure to air drying at early ages, it appears that for the fly ash concretes, this effect was partly offset by some acceleration of the strength development due to the relatively high temperature of exposure.

The resistance to chloride-ion penetration of the concrete increased with the incorporation of fly ash in the concrete as partial replacement for cement.

The reduction of the moist-curing period affected the resistance of the concretes to chloride-ion penetration but it appears that the fly ash concretes beneficiated significantly from the acceleration of the pozzolanic reaction due to the higher temperature during the drying period, and that this compensated, at least partly, for the lack of moist curing.

In general, under moist-cured conditions, the fly ash concretes showed lower absorption and volume of permeable voids values than the control concrete. However, those values increased with the reduction of the moist-curing period, and the fly ash concretes were, in general, more affected than the control concrete.

The preliminary drying shrinkage test results indicate that the control concrete tends to shrink more than the fly ash concrete when exposed to drying.

ACKNOWLEDGEMENTS

Grateful acknowledgement is made to TEAM (Technology Early Action Measures) for funding this project.

REFERENCES

1. Neville, A.M., “Properties of Concrete” Third Edition, Longman Scientific & Technical, 1981, 779 p.
2. Bilodeau, A., Sivasundaram, V., Painter, K.E., and Malhotra, V.M., “Durability of Concrete Incorporating High Volumes of Fly Ash from Sources in the U.S.” ACI Materials Journal, Vol. 91, No. 1, 1994, pp. 3-12.

3. Malhotra, V.M., and Mehta, P.K., High-Performance, High-Volume Fly Ash Concrete", Supplementary Cementing Materials for Sustainable Development Inc., 2005, 124 p.
4. Naik, T.R., Ramme, B.W., Kraus, R.N., and Siddique, R., "Long-Term Performance of High-Volume Fly Ash Concrete Pavements" ACI Materials Journal, Vol. 100, No. 2, pp. 150-155.
5. Thomas, M.D.A., Hopkins, D.S., Girn, G., Munro, R., and Muhl, E., "Use of High Volumes of Fly Ash in Concrete" Third CANMET/ACI International Symposium on Sustainable Development of Cement and Concrete, Supplementary Paper Volume, pp. 203-221.

Table 1 – Physical properties and chemical analysis of the cement and fly ash

	Cement	Fly Ash
Physical Properties		
Specific gravity	3.16	2.15
Fineness		
- passing 45 µm, %	83.1	91.8
- specific surface, Blaine cm^2/g	3643	3170
Compressive strength of 51-mm cubes, MPa		
- 7 days	23.7	
- 28 days	34.7	
Water requirement, %		95.0
Activity with cement, %		
- 7 days		88.5
- 28 days		88.8
Chemical analysis		
Silicon dioxide (SiO_2)	20.40	63.50
Aluminium oxide (Al_2O_3)	4.73	27.70
Ferric oxide (Fe_2O_3)	3.14	3.19
Magnesium oxide (MgO)	2.67	0.48
Calcium oxide (CaO)	63.9	1.33
Sodium oxide (Na_2O)	0.15	0.11
Potassium oxide (K_2O)	0.67	0.84
Titanium oxide (TiO_2)	0.22	1.74
Phosphorous oxide (P_2O_5)	0.08	0.33
Sulphur trioxide (SO_3)	2.61	0.10
Loss on ignition	2.47	0.63
Carbon	0.16	0.30

Table 2 – Grading of aggregates

Coarse Aggregate		Fine Aggregate	
Sieve Size, mm	Percentage Passing	Sieve Size, mm	Percentage Passing
19.0	100	4.75	97.2
12.7	65	2.36	85.5
9.5	40	1.18	67.7
4.75	0	0.60	43.6
		0.30	17.8
		0.15	5.5

Table 3 – Proportions of the concrete mixtures

Mix No.	W/CM	Water, kg/m^3	CM,* kg/m^3	Cement, kg/m^3	Fly Ash,		Aggregates, kg/m^3		SP, L/m^3
					%	kg/m^3	Fine	Coarse	
1	0.43	165	381	381	0	0	747	1121	2.6
2	0.43	155	358	251	30	107	750	1125	1.8
3	0.43	152	353	194	45	159	763	1144	1.7
4	0.40	142	353	194	45	159	773	1160	2.9

* CM: Total cementitious materials content

Table 4 – Properties of the fresh concrete and setting time

Mix No.	W/CM	CM, kg/m^3	Fly Ash, %	Slump, mm	Air Content, %	Unit Weight, kg/m^3	Setting Time, h:min	
							Initial	Final
1	0.43	381	0	165	1.8	2416	7:45	9:40
2	0.43	358	30	165	2.0	2390	7:20	9:20
3	0.43	353	45	100	1.2	2414	6:50	9:20
4	0.40	353	45	155	1.5	2430	10:35	12:45

Table 5 - Testing schedule of concrete

Mix. no.	Type of testing	Age of testing, days					
		0	1	3	7	28	56
1-4	Autogenous temperature rise	Fresh Concrete					
	Setting time (ASTM C 403)	Fresh Concrete					
	Compressive strength (ASTM C 39)		2 cyl.	2 cyl.	2 cyl.	2 cyl.	2 cyl.
	Resistance to the chloride-ion penetration (ASTM C 1202)					2 disks	2 disks
	Water absorption (ASTM C 642)					2 disks	2 disks
	Drying shrinkage (ASTM C 157)	Two 75x75x300 mm prisms will be exposed to air at 50% relative humidity and 23°C after 28 days of curing in lime-saturated water. One prism will be kept in water for reference purpose.					
	Effect of Curing Regime						
1- 4	*Moist Cured for 1d followed by air drying at 38°C*						
	Compressive strength			2 cyl.	2 cyl.	2 cyl.	2 cyl.
	Resistance to the chloride-ion penetration					2 disks	2 disks
	Water absorption					2 disks	2 disks
	Moist Cured for 3d followed by air drying at 38°C						
	Compressive strength				2 cyl.	2 cyl.	2 cyl.
	Resistance to the chloride-ion penetration					2 disks	2 disks
	Water absorption					2 disks	2 disks
	Moist Cured for 7d followed by air drying at 38°C						
	Compressive strength					2 cyl.	2 cyl.
	Resistance to the chloride-ion penetration					2 disks	2 disks
	Water absorption					2 disks	2 disks
	Moist Cured for 3d followed by air drying at 23°C						
	Resistance to the chloride-ion penetration					2 disks	2 disks
	Water absorption					2 disks	2 disks
	Moist Cured for 3d followed by Cycles of 38/23°C air drying						
	Resistance to the chloride-ion penetration					2 disks	2 disks
	Water absorption					2 disks	2 disks

Table 6 – Density of cylinders at 24 hours and compressive strength development of concrete under different curing regimes

Mix No.	W/CM	CM, kg/m^3	Fly Ash, %	Density at 24 h, kg/m^3	Curing regime	Compressive Strength, MPa				
						1 day	3 days	7 days	28 days	56 days
1	0.43	381	0	2456	Moist Cured at 23°C	21.2	29.7	33.6	47.2	47.9
					1 day MC* then AD* at 38°C	-	31.0	34.8	40.0	39.0
					3 days MC then AD at 38°C	-	-	37.3	40.9	42.2
					7 days MC then AD at 38°C	-	-	-	48.4	47.9
2	0.43	358	30	2434	Moist Cured at 23°C	10.9	18.5	23.2	35.7	43.0
					1 day MC* then AD* at 38°C	-	21.0	26.5	32.3	33.2
					3 days MC then AD at 38°C	-	-	29.7	38.9	38.1
					7 days MC then AD at 38°C	-	-	-	42.7	43.7
3	0.43	353	45	2436	Moist Cured at 23°C	7.7	13.0	16.9	26.1	33.4
					1 day MC* then AD* at 38°C	-	14.5	20.1	23.5	25.3
					3 days MC then AD at 38°C	-	-	22.5	30.6	30.7
					7 days MC then AD at 38°C	-	-	-	32.3	36.6
4	0.40	353	45	2425	Moist Cured at 23°C	6.7	14.9	20.4	31.7	39.3
					1 day MC* then AD* at 38°C	-	16.0	20.1	22.8	25.0
					3 days MC then AD at 38°C	-	-	27.7	34.9	35.8
					7 days MC then AD at 38°C	-	-	-	40.2	42.5

* MC = Moist cured, and AD = Air dried

Table 7 – Rapid Chloride-Ion Permeability Test (RCPT) results after different curing regimes

Mix No.	W/CM	CM, kg/m^3	Fly Ash, %	Curing regime	RCPT results, coulombs	
					28 days	56 days
1	0.43	381	0	Moist Cured at 23°C	3240	2666
				1 day MC then AD at 38°C	5576	6916
				3 days MC then AD at 38°C	4324	5155
				7 days MC then AD at 38°C	2579	3940
				3 days MC then AD at 23°C	3664	4614
				3 days MC then AD Cycles*	4510	5447
2	0.43	358	30	Moist Cured at 23°C	2213	1126
				1 day MC then AD at 38°C	4462	4285
				3 days MC then AD at 38°C	1747	1982
				7 days MC then AD at 38°C	935	896
				3 days MC then AD at 23°C	4013	3381
				3 days MC then AD Cycles*	2036	2504
3	0.43	353	45	Moist Cured at 23°C	1540	885
				1 day MC then AD at 38°C	4040	4348
				3 days MC then AD at 38°C	1815	2051
				7 days MC then AD at 38°C	1252	1850
				3 days MC then AD at 23°C	3361	3271
				3 days MC then AD Cycles*	1858	2357
4	0.40	353	45	Moist Cured at 23°C	1495	787
				1 day MC then AD at 38°C	4333	3433
				3 days MC then AD at 38°C	1339	1699
				7 days MC then AD at 38°C	1157	685
				3 days MC then AD at 23°C	2864	3462
				3 days MC then AD Cycles*	1578	1654

* 3 days of moist curing at 23°C followed by air-drying cycles of 16 hours at 38°C and 8 hours at 23°C (except weekends when the samples were kept at 38°C)

Table 8 – Absorption and volume of permeable voids of concrete subjected to different curing regimes

Mix No.	W/CM	CM, kg/m^3	Fly Ash, %	Curing regime	Absorption, %		Volume of Permeable Voids, %	
					28 days	56 days	28 days	56 days
1	0.43	381	0	Moist Cured at 23°C	5.0	4.7	12.0	11.2
				1 day MC then AD at 38°C	5.4	5.4	13.2	13.2
				3 days MC then AD at 38°C	5.2	5.0	12.7	12.1
				7 days MC then AD at 38°C	5.0	4.9	12.4	11.7
				3 days MC then AD at 23°C	5.1	4.8	12.5	11.5
				3 days MC then AD Cycles*	5.1	5.0	12.5	12.3
2	0.43	358	30	Moist Cured at 23°C	4.8	4.5	11.3	10.5
				1 day MC then AD at 38°C	5.8	5.9	13.8	13.6
				3 days MC then AD at 38°C	5.5	5.4	13.0	12.6
				7 days MC then AD at 38°C	5.3	5.3	12.6	12.3
				3 days MC then AD at 23°C	5.4	5.3	13.0	12.5
				3 days MC then AD Cycles*	5.4	5.7	12.9	13.3
3	0.43	353	45	Moist Cured at 23°C	4.7	5.2	11.3	12.1
				1 day MC then AD at 38°C	5.5	5.7	13.2	13.5
				3 days MC then AD at 38°C	5.5	5.7	12.8	13.3
				7 days MC then AD at 38°C	5.2	5.3	12.1	12.7
				3 days MC then AD at 23°C	5.3	5.4	12.7	13.1
				3 days MC then AD Cycles*	5.6	5.5	13.1	13.0
4	0.40	353	45	Moist Cured at 23°C	4.6	3.3	10.7	7.8
				1 day MC then AD at 38°C	5.3	5.4	12.5	12.8
				3 days MC then AD at 38°C	5.0	5.1	11.9	12.0
				7 days MC then AD at 38°C	5.1	5.0	11.8	11.8
				3 days MC then AD at 23°C	5.0	5.0	11.6	11.8
				3 days MC then AD Cycles*	4.9	5.0	11.3	11.8

* 3 days of moist curing at 23°C followed by air-drying cycles of 16 hours at 38°C and 8 hours at 23°C (except weekends when the samples were kept at 38°C)

Table 9 – Drying Shrinkage of Concrete after 28 Days of Initial Curing in Lime-Saturated Water

Mix No.	W/CM	CM kg/m^3	Fly Ash, %	Length Change, %					Weight Change at 112 days, %
				7 days	14 days	28 days	56 days	112 days	
1	0.43	381	0	- 0.015	- 0.023	- 0.029	- 0.040	- 0.047	- 2.56
2	0.43	358	30	- 0.012	- 0.015	- 0.024	- 0.030	- 0.036	- 2.90
3	0.43	353	45	- 0.006	- 0.015	- 0.024	- 0.025	-0.032	- 3.26
4	0.40	353	45	- 0.008	- 0.012	- 0.023	- 0.026	- 0.031	- 2.70

Table 10 – Length Change of Prisms Stored in Water

Mix No.	W/CM	CM kg/m^3	Fly Ash, %	Length Change, %					Weight Change at 112 days, %
				7 days	14 days	28 days	56 days	112 days	
1	0.43	381	0	0.001	- 0.001	+ 0.001	+ 0.002	+ 0.003	+ 0.22
2	0.43	358	30	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.
3	0.43	353	45	0.000	- 0.001	0.000	+ 0.001	+ 0.006	+ 0.28
4	0.40	353	45	- 0.001	+ 0.001	- 0.004	- 0.002	+ 0.005	+ 0.18

* N.A.: Insufficient amount of concrete to cast specimens for this test

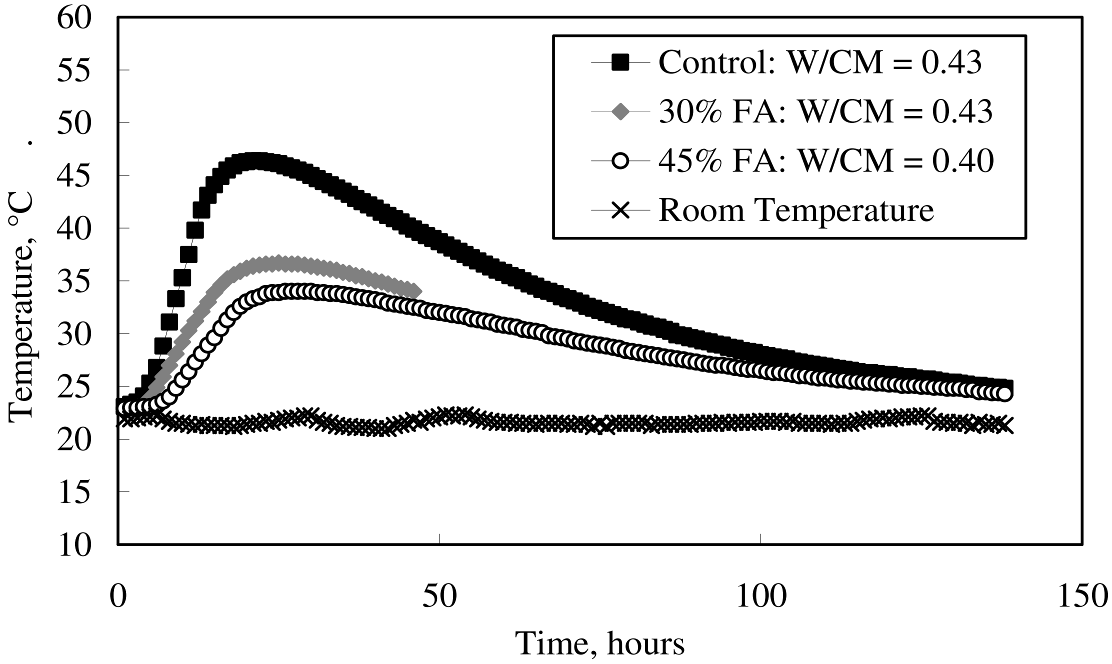

Figure 1 – Temperature of concrete in semi-adiabatic conditions

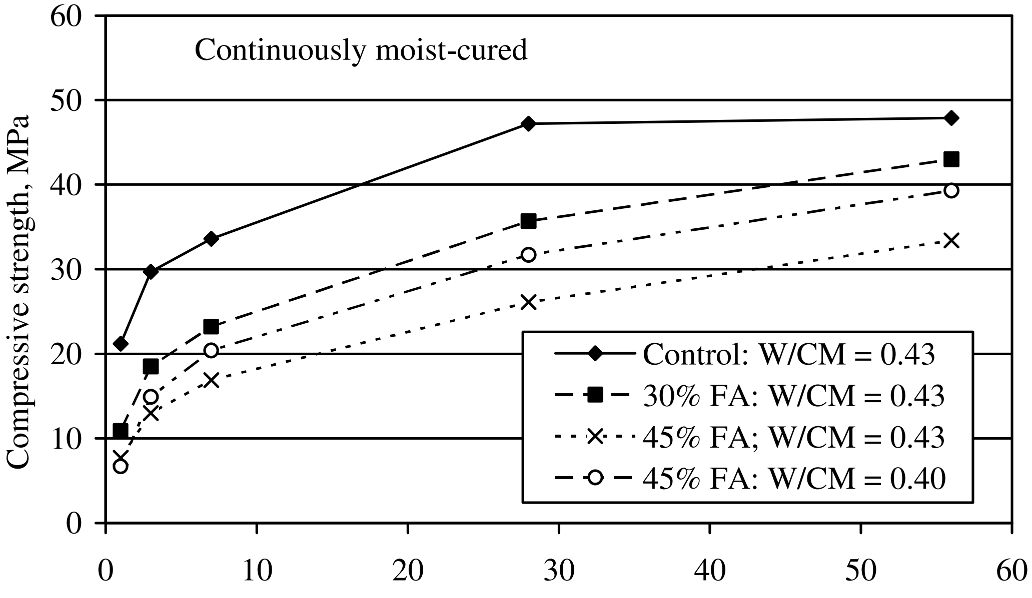

Figure 2 – Compressive strength development of concrete under moist-curing conditions

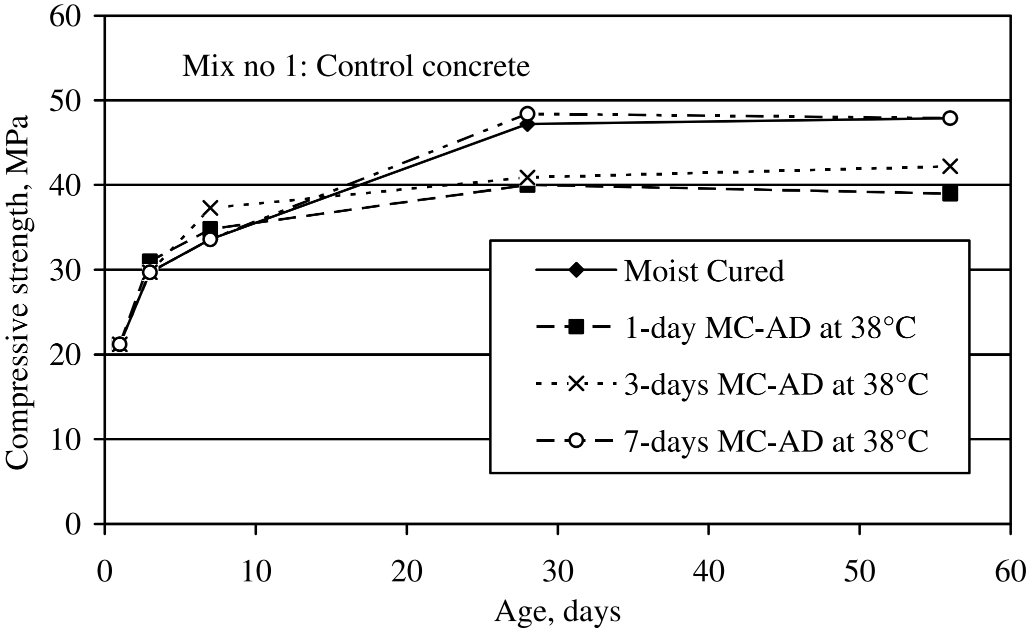

Figure 3 – Compressive strength development of control concrete under different curing regimes

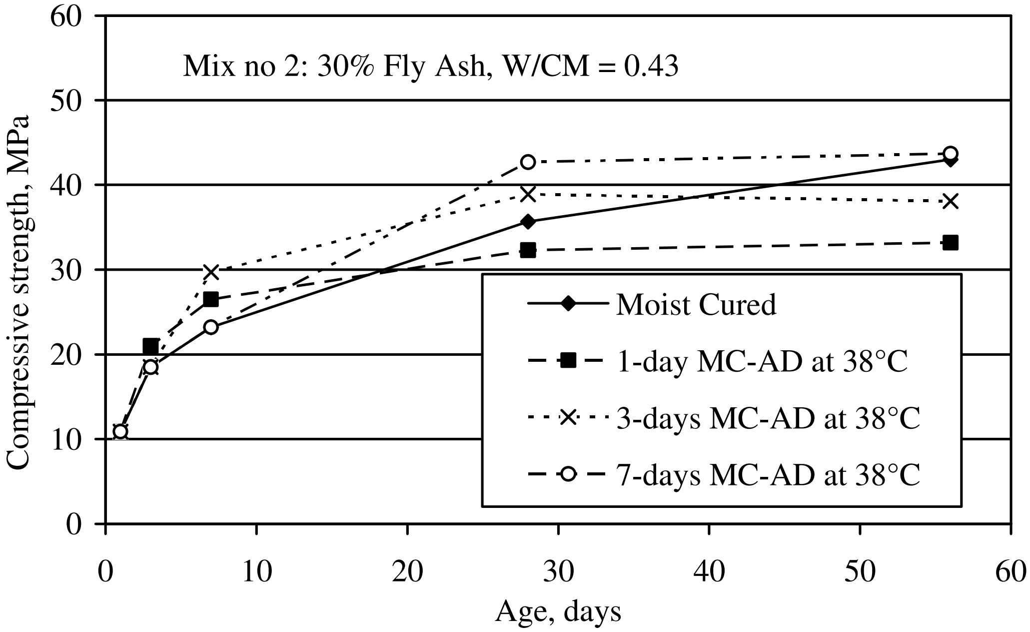

Figure 4 – Compressive strength development of concrete incorporating 30% fly ash under different curing regimes

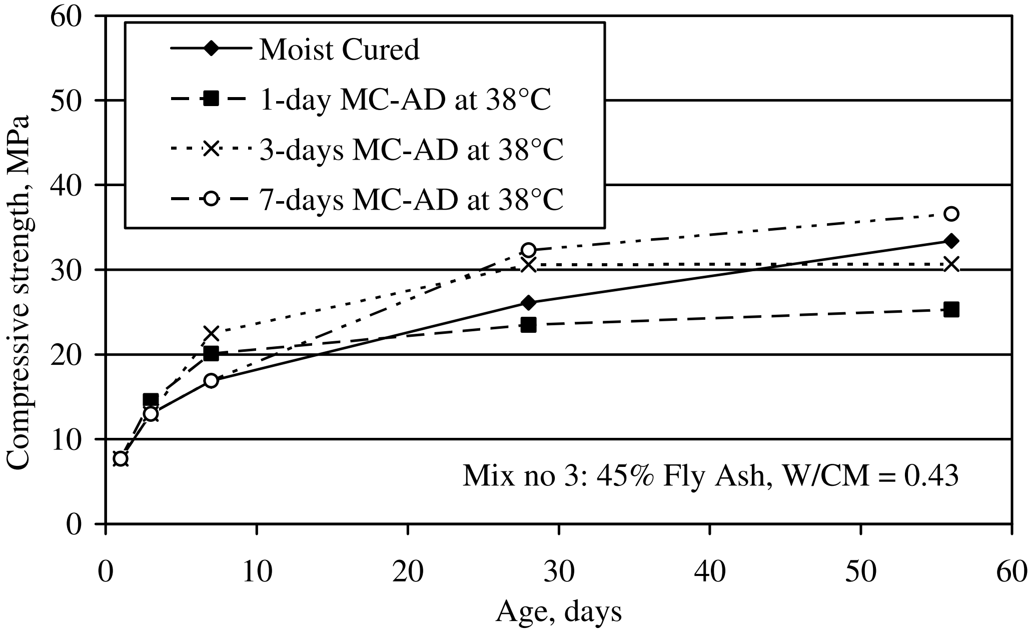

Figure 5 - Compressive strength development of concrete incorporating 45% fly ash (W/CM = 0.43) under different curing regimes

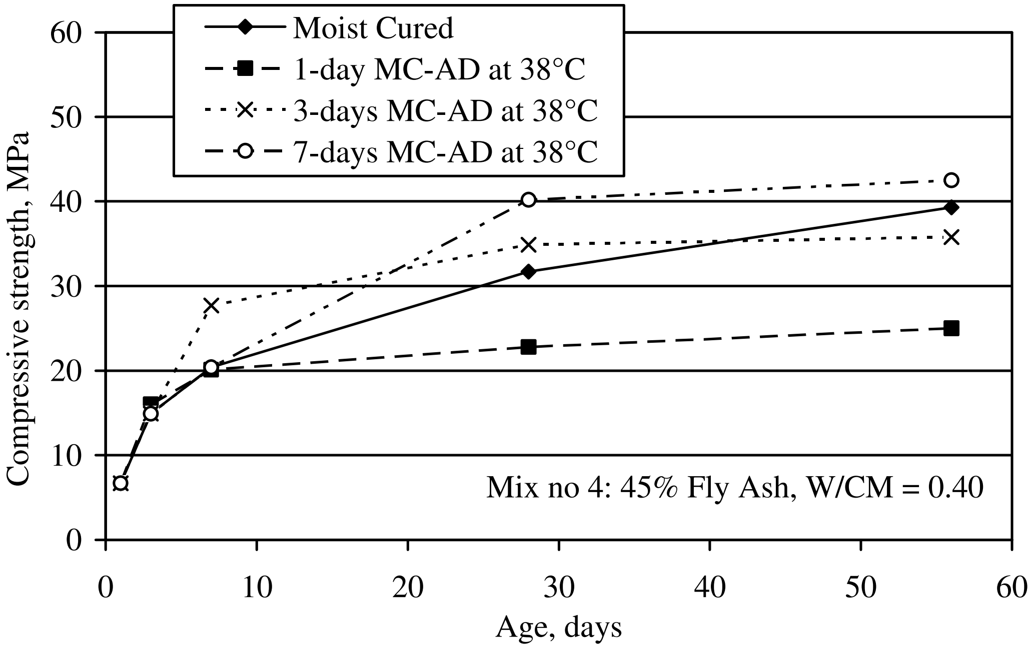

Figure 6 - Compressive strength development of concrete incorporating 45% fly ash (W/CM = 0.40) under different curing regimes

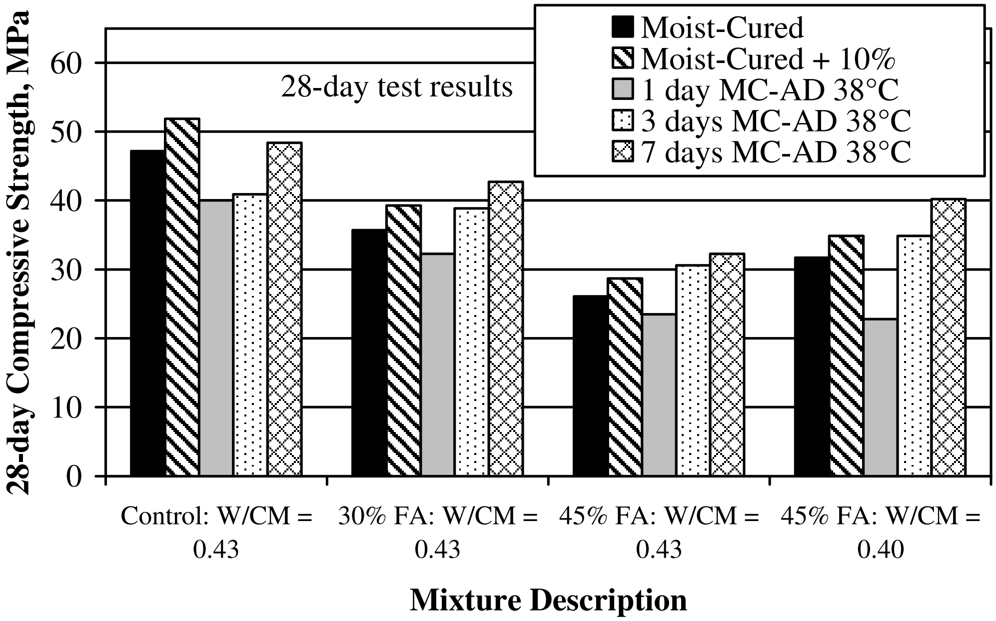

Figure 7 – Compressive strength at 28 days of the concrete specimens exposed to the various curing regimes compared to theoretical moist-cured specimens tested in dry condition (10 per cent increase)

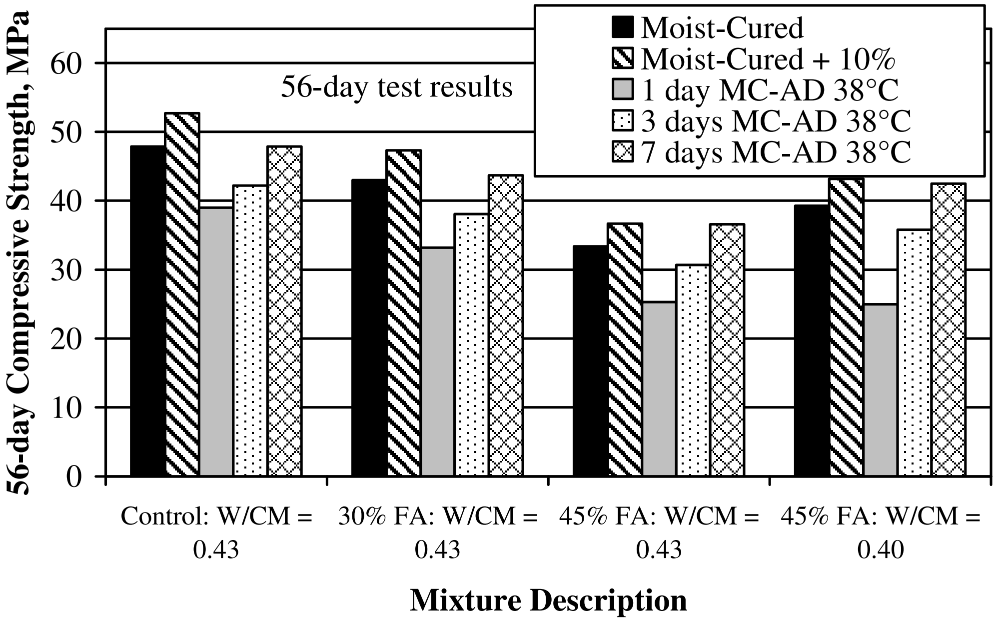

Figure 8 – Compressive strength at 56 days of the concrete specimens exposed to the various curing regimes compared to theoretical moist-cured specimens tested in dry condition (10 per cent increase)

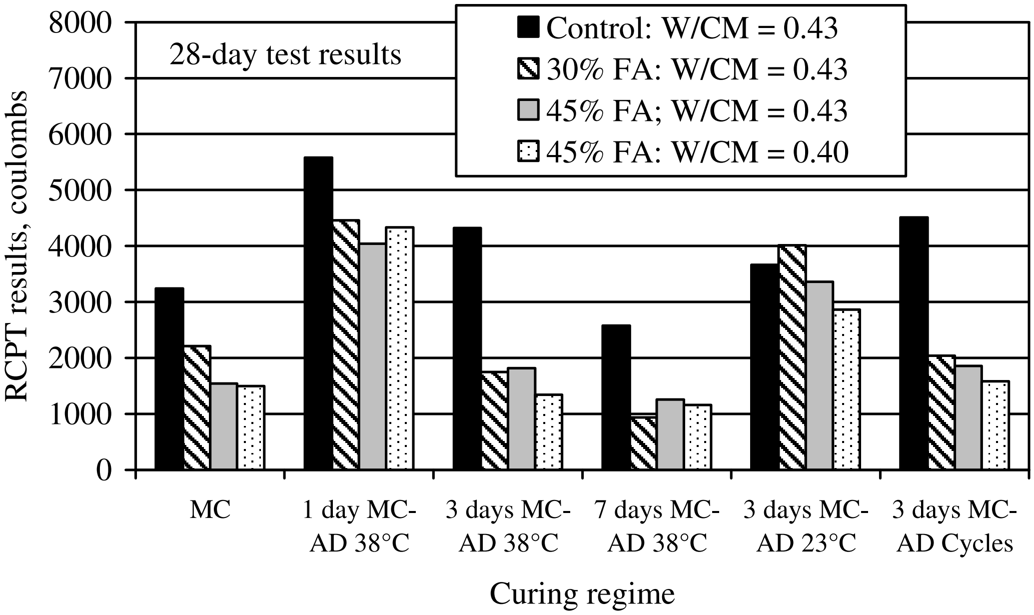

Figure 9 – Rapid chloride-ion permeability test results at 28 days for concrete subjected to different curing regimes

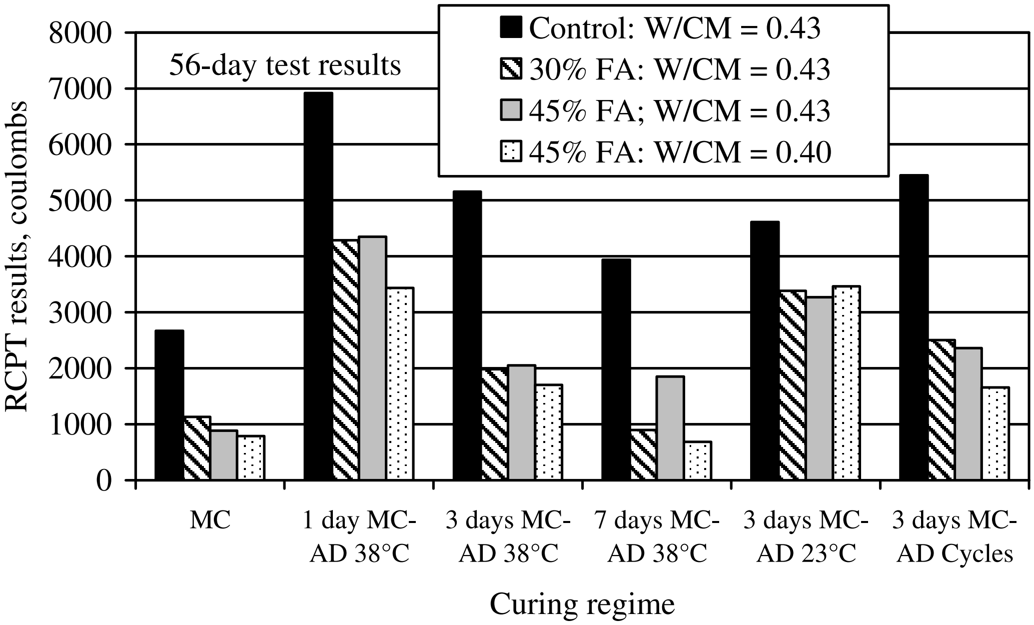

Figure 10 – Rapid chloride-ion permeability test results at 56 days for concrete subjected to different curing regimes

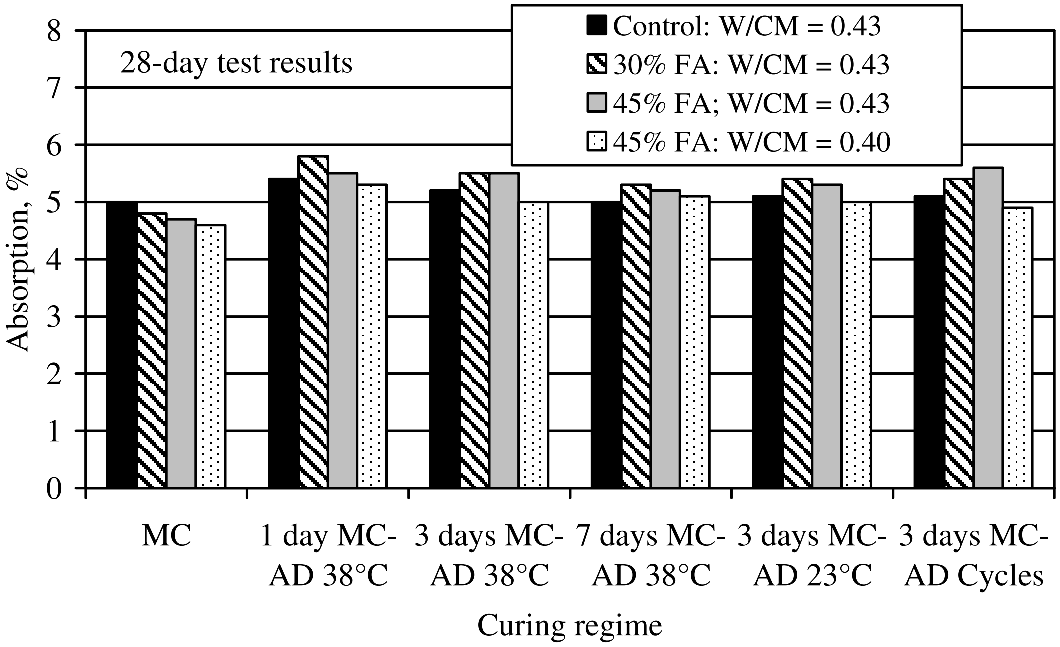

Figure 11 – Absorption at 28 days of concrete subjected to different curing regimes

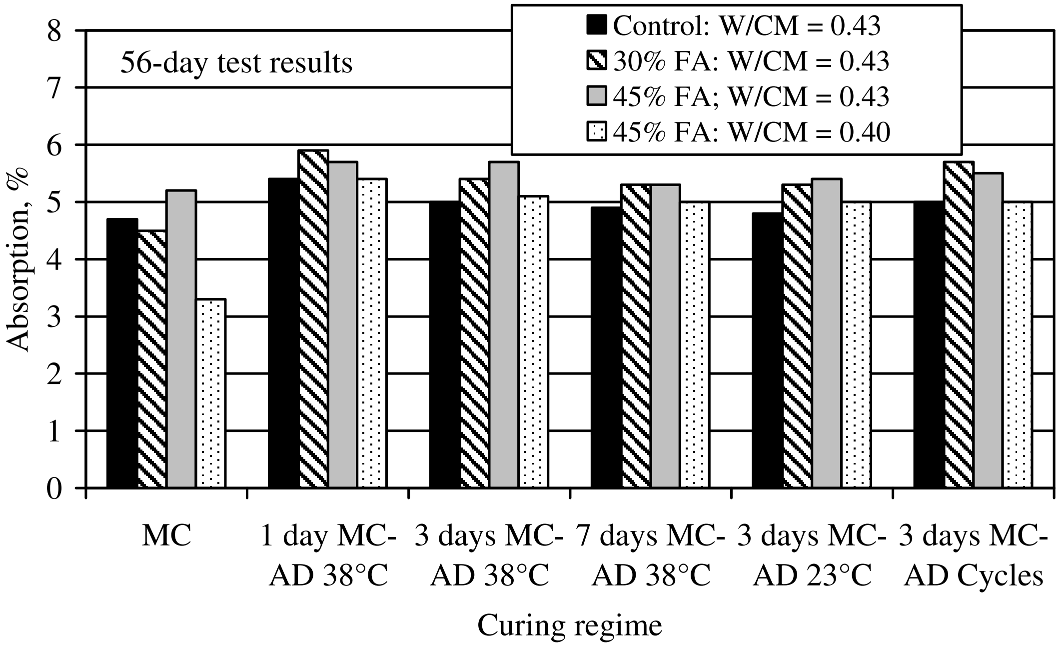

Figure 12 – Absorption at 56 days of concrete subjected to different curing regimes

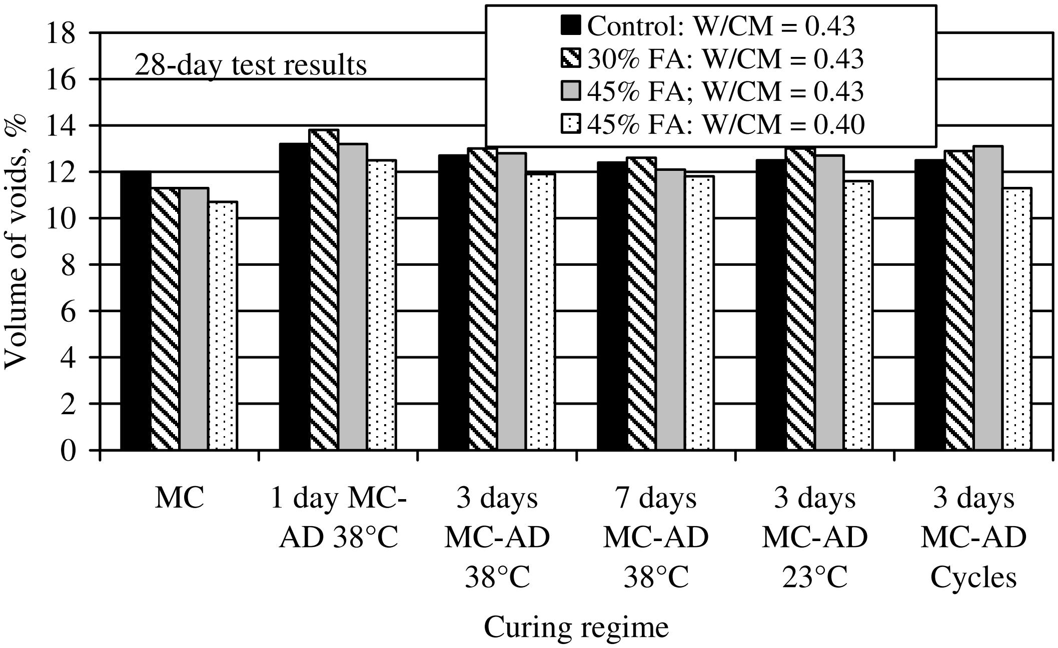

Figure 13 – Volume of permeable voids at 28 days of concrete subjected to different curing regimes

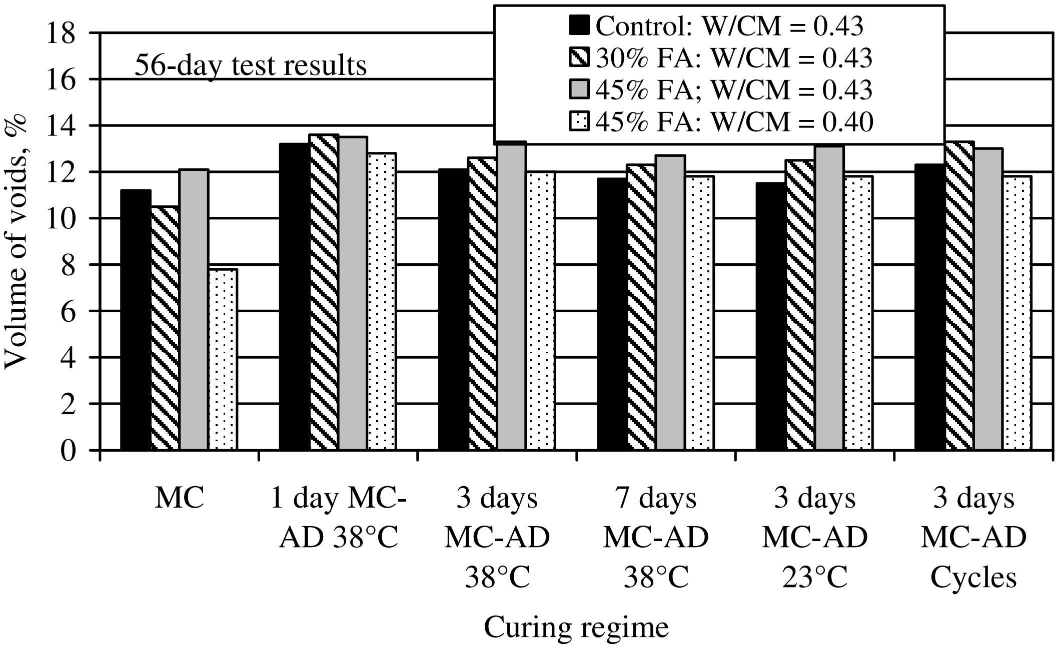

Figure 14 – Volume of permeable voids at 56 days of concrete subjected to different curing regimes

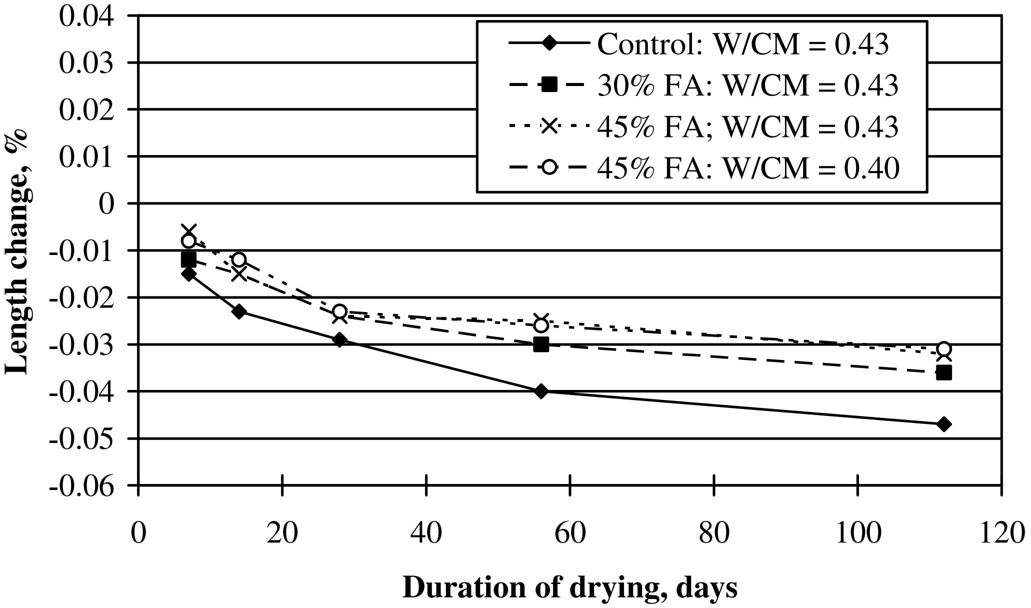

Figure 15 – Drying shrinkage test results of concrete