Final Report for a Collaborative Project on

HVFAC for Structural Applications

– A Study on Technology Adaptation

(Under CII – CANMET - CIDA HVFAC Project)

at Bengal Engineering and Science University, Shibpur,

(Formerly Bengal Engineering College, Estd. 1856)

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INTRODUCTION

Portland cement is an essential component of concrete, and India currently produces about 100 million tonnes of this material annually; the manufacturing of portland cement in India directly results in the emission of over 80 million tonnes of CO_2 annually.

Without the introduction of new technologies and practices to use larger proportions of supplementary cementing materials (SCMs) such as fly ash, either directly in concrete production, or through the increased use of blended cements incorporating significant percentages of SCMs, the production of ordinary portland cement, will increase significantly in India to meet the rapidly increasing demand from the concrete industry. Consequently, this would translate into a significant increase of CO_2 emissions.

The High-Volume Fly Ash Concrete (HVFAC) technology developed at CANMET, Canada (1-14) utilizes proper mixture proportioning and judicious selection of locally available materials and chemical admixtures to minimize the amount of ordinary portland cement required to produce high-quality concrete for different types of applications, while continuing to meet requirements for performance, cost and practicability.

The objective of the present project is to adapt the Canadian technology of HVFAC to the Indian context using Indian materials, specifically materials from West Bengal. The specific goal of the project is to determine the optimum fly ash content (30 to 50%) in concretes made with ordinary portland cement (OPC) and portland-pozzolona cement (PPC) designed to meet the requirements of concrete grades M20, M40 and M60.

SCOPE

Concrete of grades M20, M40 and M60 (nominally 20, 40 and 60 MPa) using fly ash with OPC and PPC were investigated in this project. For each grade of concrete made with OPC, four concrete mixtures were made, a control concrete without fly ash, and concrete incorporating 30, 40 and 50% fly ash. For each grade of concrete made with PPC, three concrete mixtures were made, one made with PPC only, one with the cementitious materials incorporating 40% fly ash, and one with the cementitious materials incorporating 50% fly ash. In addition to this, for grade M40, both for concretes made with OPC and PPC, mixtures with the cementitious materials incorporating 55% fly ash were made. For each concrete mixture, the compressive strength at 1, 3, 7, 28, 56 and 91 days, splitting tensile strength, flexural strength and rapid chloride penetrability at 28 and 91 days were determined.

MATERIALS

Cement

Two types of cements were used i.e. 53 grade ordinary Portland cement (OPC), as per IS 12269, manufactured by Ambuja Cement and portland-pozzolona cement (PPC), as per IS 1489, manufactured by Ambuja cement, containing approximately 30% fly ash from Garden Reach[1]. Their physical properties and chemical analysis are given in Table 1.

Fly ash

The fly ash used is from Garden Reach CESC thermal power station, Kolkata, West Bengal. Its physical properties and chemical analysis are given in Table 1.

Aggregates

Two sizes of coarse aggregates were used in this project i.e. 20-mm graded aggregate as per IS 383 was used for grade M20 concrete, and 16-mm graded aggregate as per IS 383 was used for grades M40 and M60 concretes. A river sand, (Grading zone-II conforming to IS 383) was used as fine aggregates in all grades of concrete investigated. The physical properties of the aggregates are given in Table 2.

Admixtures

ASTM Type-A, lignosulfonated based water reducing admixture, manufactured by Pidilite Industries Ltd, India, was used for M20 grade of concrete, and ASTM Type-F (napthalene formaldehyde based superplasticizer) manufactured by FOSROC India Ltd, was used for grades M40 and M60 concretes.

Mixture Proportions

The proportions of the concrete mixtures are summarized in Table 3 to 8. For the concrete mixtures of grade M20, a total weight of cementitious materials of approximately 350 kg/m^3 was used. For concretes of grade M40 and grade M60, total weights of cementitious materials of approximately 400 kg/m^3, and 450 kg/m^3 were used, respectively. Different proportions of fly ash were used in the concrete mixtures. For the different grades of concretes made with OPC, control concrete without fly ash, and mixtures incorporating 30, 40 and 50% fly ash as replacement for OPC were produced. For the M40 concrete, an additional mixture incorporating 55% fly ash was also made. This particular mixture is more similar to the typical high-volume fly ash concrete (HVFAC) mixture developed by CANMET (1-13). For the different grades of concrete made with PPC, a mixture was made using the PPC as is, and mixtures were made with partly replacing PPC with fly ash to bring the total proportion of fly ash in the cementitious materials content of the mixtures to 40, and 50%. Again an additional mixture was made with the total proportion of fly ash in the cemetitious materials content of the mixture at 55%. To determine the percentage of replacement of PPC by fly ash in the mixtures made with the PPC to achieve the specific proportions of fly ash in the cementitious materials content (40, 50 and 55%), it was assumed that the PPC incorporated 30% fly ash.

The cementitious materials content was kept approximately constant for each grade of concrete. However, the water content, and to some extent, the dosage of admixture (either water reducer or superplasticizer) were adjusted to get the target slump and

[1] Information from the cement producer.

similar strengths for all the concrete mixtures of the same grade. Consequently, the water-to-cementitious materials ratios of the mixtures varied depending on the percentage of fly ash used.

PREPARATION AND CASTING OF TEST SPECIMENS

All the concrete mixtures were mixed in a laboratory drum concrete mixer. From each concrete mixture, a number of 150x150x150-mm cubes, 100x200-mm cylinders and 100x100x500-mm prisms were cast for the determination of the compressive, flexural and splitting tensile strengths, and the chloride-ion penetrability. Two batches of the same concrete mixture were needed to make all the samples.

The specimens were cast in two layers and were compacted using an internal vibrator. They were demolded after 24 hours, and were transferred to a water tank until required for testing.

TESTING OF THE SPECIMENS

The slump, and the compressive, splitting tensile and flexural strengths were determined according to the Indian standard procedures. The chloride-ion penetrability (RCPT) was performed according to the ASTM C 1202 standard test method.

RESULTS AND ANALYSIS

Properties of fresh concrete

The properties of fresh concrete such as the unit weight, the initial slump and the slump after 30 minutes of the mixtures are presented in Table 3 to 8.

Grade M20 Concrete made with OPC

Table 3 shows the properties of fresh concrete of grade M20 concrete made with OPC and Garden Reach fly ash (30, 40 and 50% as replacement of cement by mass). The results show that the unit weight and slump of concrete ranged from 2445 to 2505 kg/m^3, and from 75 to 105 mm, respectively.

For similar total weight of cementing materials (350 kg/m^3) and similar range of slump, the increase of fly ash content from 30 to 50% decreased the water content from 165 to 149 kg/m^3, and the w/cm from 0.48 to 0.43 (Mix. 2 to 4), whereas the corresponding values for the control mixture without fly ash are 174 kg/m^3 and 0.50 respectively (Mix. 1)

Grade M40 Concrete made with OPC

Table 4 shows that the unit weight and initial slump of the concrete mixtures of grade M40 concrete ranged from 2405 to 2480 kg/$m^3$and from 105 to 120 mm, respectively.

The results show that for similar total weight of cementitious materials and similar range of slump, the increase of fly ash content decreases the water content and the w/cm of the concrete. For example, for concrete mixtures made with 400 kg/m^3 of cementitious materials, the increase of fly ash content from 30 to 50% decreased the w/cm from 0.36 to 0.32 to obtain a slump of about 100 mm (Mix. 6 to 8). The higher slump registered for HVFAC (Mix. 9) is mainly due to the higher dosage of the superplasticizer.

The slump was reduced significantly after 30 minutes, and the reduction was similar for all mixtures. The high ambient temperature (around 30ºC) must have had a strong effect on the slump loss with time.

Grade M60 Concrete made with OPC

Table 5 shows that the unit weight and the initial slump of Grade M60 concretes ranged from 2445 to 2465 kg/m^3 and from 95 to 115 mm, respectively.

The results show that for similar slump, the use of fly ash resulted in a significant decrease of the dosage of superplasticizer. The results also show that the use of fly ash reduced the water demand of the concrete to achieve certain workability. However, the water reduction rate was lower compared to that observed for lower Grades of concrete. For example, the use of fly ash in concrete of Grade M60 reduced the water content from 147kg/m^3 for the control mixture to 130 kg/m^3 for the 50% fly ash concrete whereas, for concrete of Grade M20 the corresponding reduction was from 174 to 149 kg/m^3.

Again, a significant slump loss was noticed for all the concretes.

Grade M20 Concrete made with PPC

Table 6 presents the properties of the fresh concrete of grade M20 concrete made with PPC and different percentages of Garden Reach fly ash. The results show that the unit weight and initial slump ranged from 2370 to 2420 kg/m^3 and from 80 to 110 mm, respectively. As it was observed for the concrete made with OPC, the increase in the proportion of fly ash in the cementitious materials content reduced the water demand and the w/cm of the mixtures. However, to achieve similar slump, these concretes required higher water demand (higher w/cm) than the corresponding mixtures made with OPC (Table 3). This is possibly due to the fact that the fly ash incorporated in the blended cement gets finer during the production of the PPC because of the intergrinding process with the clinker, which results in increased water demand compared to fly ash used as separate ingredient in the concrete mixer. Another possibility could be that the cement part itself of the PPC is slightly finer than that of the OPC; this would also result in higher water demand. A third possibility could also be that the percentage of fly ash in the PPC is a bit less than 30%. The value of 30% was based on information from the cement producer, and was used for the calculation of the percentage of replacement to achieve specific fly ash contents in the mixtures. In spite of the good control from the cement producer, there are probably some slight variations in the actual percentage of fly ash in the PPC. This would also influence the water demand of the cement. A combination of all the above factors is also possible.

Similarly to the OPC mixtures, all concretes showed significant slump loss after 30 minutes.

Grade M40 Concrete made with PPC

Table 7 shows the properties of the fresh concrete of grade M40 concrete made with PPC and different percentages of Garden Reach fly ash. The results show that the unit weight and initial slump of these concretes ranged from 2420 to 2480 kg/m^3 and from 95 to 125 mm, respectively. As observed for grade M20 concrete, these concrete mixtures required higher dosage of superplasticizer and higher water demand to achieve similar slump as the corresponding mixtures made with OPC cement (Table 4). Once again, a significant slump reduction was observed after 30 minutes.

Grade M60 Concrete made with PPC

Table 8 presents the properties of the fresh concrete of grade M60 concrete made with PPC and different percentages of Garden Reach fly ash. The results show that the unit weight and initial slump of these concretes ranged from 2445 to 2455 kg/m^3 and from 85 to 110 mm, respectively.

As for grades M20 and M40 concrete, the use of PPC resulted in higher water demand or higher dosage of superplasticizer to achieve similar slump as that of the mixtures made with OPC (Table 5). Again, significant slump reduction after 30 minutes was noticed for all concretes.

Properties of hardened concrete

The compressive strength at 1, 3, 7, 28, 56 and 91 days, the splitting tensile and flexural strengths, and the rapid chloride-ion penetrability (RCPT) of the concrete investigated are presented in Tables 9 to 20.

Grade M20 Concrete made with OPC

Compressive strength

Table 9 shows that the 28 days compressive strength of the concrete of Grade M20 made with OPC ranged from 38.1 to 45.7 MPa. This shows that most of these concretes were over-designed, performing as Grade M35 or M40 concretes. The cementitious materials content could probably have been around 300 kg/m^3 instead of 350 kg/m^3, and still meet the M20 requirements.

The results show that the mixtures incorporating 30 and 40% fly ash as cement replacement, developed 28-day strength slightly higher than that of the control. The relatively high strength of these fly ash mixtures is partly due to their lower w/cm compared to that of the control mixture, resulting from the reduced water demand. The high strength level of the fly ash mixtures indicates also that the Garden Reach fly ash used in this project is quite reactive. At 91 days, these two fly ash mixtures showed strength values significantly higher than the control concrete. However both fly ash concretes had significantly lower compressive strength at early ages than the control. This was expected because it is well known that the reaction of fly ash is a slower process than the hydration of cement, resulting in a slower strength development of fly ash concrete compared to OPC concrete at early ages but faster at later ages. The concrete made with 50% fly ash showed a compressive strength somewhat lower than that of the control at 28 days and even at 91 days, and of course significantly lower at early ages. This indicates that the 50% fly ash mix was not properly designed to achieve the same 28-day strength as that of the control. However, the 50% fly ash concrete did meet the M20 requirement as well. Both the 40 and 50% fly ash mixtures had not set yet at one day. This is probably due to the retarding effect of the water-reducing admixture. The dosage of the admixture was probably too high for the amount of OPC in those two mixtures; it is mainly the amount of OPC that controls the setting time since the fly ash contribution to strength development at one day is negligible. Some results cannot be explained, for example the higher 56-day strength of the control mix compared to its 91-day strength; these are probably due to some experimental errors.

In general, the results show that it is possible to replace up to 50% of cement by fly ash and still develop adequate early age strength (3 days), 28-d compressive strength well above grade M20 requirements, and relatively high long-term strengths.

Splitting tensile and Flexural strength

Table 10 shows that the control and the 30% fly ash concretes developed similar splitting tensile and flexural strength at 28 and 91 days. The 40% fly ash concrete showed similar strengths at 28 days but higher strengths at 91 days when compared to the splitting tensile and flexural strength developed by the control concrete. On the other hand, the 50% fly ash concrete developed lower strengths at 28 days but similar strengths at 91 days as those of the control concrete.

Chloride-ion penetrability

Table 10 shows that the 28-d chloride-ion penetrability test result of the control concrete was 5290 coulombs, considered as a high according to ASTM C 1202. The 28-d chloride-ion penetrability of the fly ash concretes ranged from 1450 to 1800 coulombs, which is considered as low. These results show that for similar 28-d compressive strength, the fly ash concrete will demonstrate significantly lower chloride-ion penetrability compared to that of the control concrete, and then, be potentially more durable in terms of corrosion resistance. It is also noted that chloride penetrability may be further reduced with increase of age of samples. At 91 day, fly ash concrete showed very low chloride-ion penetrability ranging from 500 to 630 coulombs, whereas, the control concrete showed moderate chloride-ion penetrability of 3100 coulombs.

Grade M40 Concrete made with OPC

Compressive Strength

Table 11 presents the compressive strength at 1, 3, 7, 28, 56 and 91 days of concrete of grade M40 made with OPC and Garden Reach fly ash. The table shows that the 28-day compressive strength of the concretes ranged from 48.8 to 58.9 MPa, which is above the requirements for grade M40 concrete.

The results show the same trend as that observed for concrete mixtures of Grade M20; the fly ash concretes developed lower early ages strengths, and generally higher strengths at later ages compared to those of the control concrete. The results also show that the 30 and 40% fly ash concretes developed significantly higher strengths at 28 days and beyond, while the 50% fly ash and the HVFAC (typical CANMET mix) developed similar strengths at 28 days and beyond, when compared to the strength values of the control concrete. This shows that it is possible to substitute up to 55% ordinary portland cement by Garden Reach fly ash and still obtain a concrete that develops acceptable early age strength, and similar or higher strengths at 28 days and at later ages compared to those of a concrete of grade M40 made with portland cement only.

Splitting tensile and Flexural strength

Table 12 shows that, in general, the control and the fly ash concretes developed similar 28-d splitting tensile strengths. At 91 days, the fly ash concretes developed higher splitting tensile strength. The flexural strength followed the same trend as that observed for splitting tensile strength, except that the 40% fly ash developed significantly higher 28-d flexural strength, and for some reasons, the HVFAC developed relatively lower 28 and 91-d flexural strengths than those of the control concrete.

Chloride-ion penetrability

Table 12 shows that the 28-d chloride-ion penetrability test result of the control concrete was 1860 coulombs, considered as low according to ASTM C 1202. This is much lower than that of the control M20 concrete (5290 coulombs), and is the result of the significantly lower w/cm of the M40 mix.

The 28-d test results of the fly ash concretes ranged from 890 to 1460 coulombs, considered as very low, to low chloride-ion penetrability. These results show again that for similar 28-d compressive strength, the fly ash concrete will show lower value of chloride-ion penetrability compared to that of the control concrete. At 91 day, fly ash concrete showed very low chloride-ion penetrability (230 to 330 coulombs) compared to the low chloride-ion penetrability demonstrated by the control concrete (1360 coulombs).

Grade M60 Concrete made with OPC

Compressive strength

Table 13 shows the compressive strength at 1, 3, 7, 28, 56 and 91 days of the control and fly ash concretes of grade M60 made with OPC. The control and the 40% fly ash mixture barely met the M60 requirements with 28-day compressive strengths of 60.6 and 60.3 MPa, respectively. Both the 30% and the 50% fly ash mixtures met easily the M60 requirements with 28-day compressive strengths of 68.1 and 70.2 MPa, respectively.

The results show that it is possible to substitute up to 50% of cement by fly ash, and obtain adequate early-age strengths, and similar or higher strengths at 28 days and at later ages, compared to those of a control OPC concrete of grade M60. However, as it is the case for all grades of concrete, this can be done only by using a significantly lower w/cm for the fly ash concrete compared to that of the control OPC concrete.

Splitting tensile and Flexural strength

The control concrete developed 28, and 91-d splitting tensile strengths of 4.1, and 5.6 MPa, respectively. For the fly ash concretes, the 28 and 91-day splitting tensile strengths ranged from 3.7 to 4.6, and from 3.5 to 4.8 MPa, respectively (Table 14); the values being generally reduced with increasing the fly ash content. Surprisingly, the fly ash concretes developed lower splitting tensile strengths than those of the control concrete at both ages, with the exception of the 28-day result of the concrete made with 40% fly ash. The same trend was observed for the flexural strength, except for the 30% fly ash concrete, which developed higher values than the control concrete at both ages. The 28, and 91-d flexural strengths of the control were 7.5, and 8.7 MPa, respectively; those of the fly ash concretes ranged from 6.7 to 8.8, and from 6.9 to 9.4 at 28, and 91 days, respectively.

Chloride-ion penetrability

The 28-d chloride-ion penetrability test result of the control concrete was 1970 coulombs, considered as low according to ASTM C 1202 (Table 14). This shows that low chloride-ion penetrability can be obtained for control concrete by reducing the w/c to relatively low values. However, the improvement cannot go beyond a certain limit, especially at 28 days, and thus, the easiest and possibly only way to reduce the coulomb values of concrete to, for example, less than 1500 coulombs at 28 days, is by using supplementary cementing materials such as fly ash.

The 28-d chloride-ion penetrability of the fly ash concretes ranged from 530 to 1140 coulombs considered as low, to very low chloride-ion penetrability. The value of 1140 Coulomb for a 50% fly ash concrete with a w/cm of 0.28 seems to be very strange because much higher than expected. This is probably due to an experimental error. However, at 91 days all the fly ash concrete showed coulomb values of less than 300, which is close to the value considered by ASTM C 1202 as a negligible chloride-ion penetrability.

Grade M20 Concrete made with PPC

Compressive strength

Table 15 presents the 1, 3, 7, 28, 56 and 91-d compressive strength test results of grade M20 concrete mixtures made with PPC and Garden Reach fly ash. The results show that the 1-d compressive strength decreased significantly with increasing fly ash content. However, at 3 days and beyond, the increase in fly ash content did not significantly decrease the compressive strength. In fact, at 28 days all concretes developed similar compressive strength of about 40 MPa. As it was the case for grade M20 concrete made with OPC, this shows that these mixtures were over-designed for a concrete of grade M20, and the total cementitious materials could have been reduced.

It was already mentioned that the PPC used in this study contains about 30% fly ash from the same source at Garden Reach, Kolkata. When comparing the results of concretes made with PPC with those of similar grade of concrete but made with OPC (Table 9), it can be seen that in general, the use of PPC increased the early age strength (up to 7 days), and reduced the strength at 28 days and beyond. The slightly higher early-age strength up to 7 days of the PPC concrete is probably explained by the same possible reasons stated previously for the water demand: finer fly ash due to intergrinding process, finer cement part of the PPC, slightly lower percentage of fly ash in the PPC than what was assumed, or a combination of those factors.

The results clearly show that it is possible to increase the proportion of fly ash in a given amount of cementitious materials by replacing part of PPC, and produce concrete having a performance comparable to that of a concrete that would incorporate the same amount of cementitious materials and the same proportion of fly ash as partial replacement for OPC.

Splitting tensile and Flexural strength

Splitting tensile and flexural strength of grade M20 concretes made with PPC (Table 16) were found similar to the corresponding concretes made with OPC (Table 10) both at 28 days and 91 days. However, there is a tendency of showing slightly higher values for samples made with PPC but that variation may be within the range of experimental deviations.

Chloride-ion penetrability

Table 16 shows that the concrete mixtures of grade M20 made with PPC developed 28, and 91-d coulomb values ranging from 940 to 1430, and from 340 to 540 coulombs, respectively. According to ASTM C 1202, these values are considered to be equivalent to low/very low chloride-ion penetrability. When comparing these values to those of the same grade of concrete but using OPC, it was observed that in general, the concretes with PPC developed lower coulomb values, which again could be due to the greater fineness of the fly ash incorporated in the PPC that would result in finer cement paste microstructure, and consequently lower permeability.

Grade M40 Concrete made with PPC

Compressive strength

Table 17 shows that the concrete mixtures of Grade M40 made with PPC developed 1, 28, and 91-d compressive strengths ranging from 11.6 to 20.8, 46.2 to 52.9, and from 55.5 to 61.3 MPa, respectively. These concretes comfortably met the strength requirement of grade M40. When comparing these results to those of corresponding concretes made with OPC (Table 11), it again appears that the use of PPC resulted in higher early-age strength (up to 7 days) and lower later-age strength. The increase in the early-age strength is again probably due to the reasons stated above. The decrease in the strength at later age is mainly due to the increased w/cm of the concretes made with PPC compared to that of the concrete made with OPC.

For the HVFAC that was made with similar w/cm of 0.32 in both cases (using OPC and PPC), it was observed that the use of PPC resulted in increased early-age strength and similar later-age strength.

Splitting tensile and Flexural strength

Table 18 shows that the splitting tensile strength of the concrete was about 4 MPa at 28 days and about 4.5 MPa at 91 days. The 28 and 91-d flexural strengths ranged from 5.3 to 6.5 and from 6.5 to 8.0 MPa, respectively. When comparing these values to those of concretes made with OPC (Table 12), it appears that they are, in general, similar, except the 91-d flexural strength of the 40 and 50% fly ash concretes that were slightly higher for the concretes made with PPC.

Chloride-ion penetrability

Table 18 shows that the 28 and 91-d chloride-ion penetrability test results of the concretes ranged from 840 to 1810, and from 270 to 360 coulombs, respectively. When comparing these values to those of concretes made OPC (Table 12), it appears that the use of PPC resulted in lower 28-d coulomb values, especially for the 40 and 50% fly ash concretes. As mentioned earlier, this could be due to the increased fineness of the fly ash incorporated in the PPC.

Grade M60 Concrete made with PPC

Compressive strength

Table 19 shows the compressive strength of the grade M60 concretes made with PPC. The results show that the 1, 28 and 91-d compressive strengths ranged from 18.7 to 23.7, 52.1 to 65.9, and from 67.8 to 69.8 MPa, respectively. It appears that the 50% fly ash mix did not meet the requirement of grade M60 concrete. However, considering the results obtained by this concrete at other ages, the lower 28-day strength result could be due to experimental error.

When comparing these results to those of corresponding concretes made with OPC (Table 13), it appears that the use of PPC resulted in significantly higher 1-d strength, but somewhat lower 91-d strength. These results confirms those obtained for the lower grades of concrete, and are, again, probably due to the same reasons stated earlier.

Splitting tensile and Flexural strength

Table 20 shows that the 28, and 91-d splitting tensile strengths of the concretes ranged from 4.0 to 5.2, and from 5.1 to 5.9 MPa, respectively; the corresponding flexural strengths ranged from 7.3 to 7.8, and from 7.3 to 7.7 MPa, respectively. This results show that the increase in strengths from 28 to 91 days was marginal due to the above-mentioned reasons (combination of lower w/cm, higher cementitious materials and fineness of fly ash).

When comparing these results to those of corresponding concretes made with OPC (Table 14), it appears that the splitting tensile strength values were generally higher for the concretes made with PPC, and this was not expected. For flexural strength values, the use of PPC generally resulted in similar 28-d values and lower 91-d values, which follow the same trend as for the compressive strength.

Chloride-ion penetrability

Table 20 shows that all concretes developed very low chloride-ion penetrability at both ages. As mentioned above, the fact that the fly ash is possibly finer in PPC, would result in finer microstructure in the cement paste, which would decrease the permeability of the concrete. Therefore, the use of PPC cement in high grades of concrete (M60) will further reduce the chloride-ion penetrability at early age (28 days in this case) but marginally affect the chloride-ion penetrability at later ages.

CONCLUSIONS

Based on the results obtained from this study, the following conclusions can be drawn:

1. For similar Grade of concrete, similar range of slump, and similar cementitious materials contents, the water requirement and consequently the w/cm decreased with increasing fly ash content.
2. For similar slump and similar fly ash content, the w/cm decreased with increasing total weight of cementitious materials.
3. It is possible to design a concrete incorporating up to 50% fly ash that meets the strength requirement of grades M20, M40 and M60 concrete; such concrete will develop acceptable early ages strength, higher strength at later ages, and significantly lower chloride-ion penetrability compared to control concretes of similar grade made with OPC only.
4. It is possible to increase the proportion of fly ash in a given amount of cementitious materials by replacing part of PPC, and produce concrete having a performance comparable to that of a concrete that would incorporate the same amount of cementitious materials and the same proportion of fly ash as partial replacement for OPC.
5. For the same grade of concrete, the same total amount of cementitious materials, and the same proportion of fly ash, the use of PPC in combination with fly ash resulted in increased dosages of water reducer and

superplasticizer, and/or higher w/cm in order to achieve similar workability, compared to concrete in which blends of OPC and fly ash were used. This could be explained by a finer fly ash in the PPC due to intergrinding process, finer cement part of the PPC, slightly lower percentage of fly ash in the PPC than what was assumed, or a combination of those factors.

6. The use of PPC resulted in increased compressive strength at early ages, but lower compressive strength at later ages. These changes were more significant for higher grades of concrete. The slightly different behavior in strength development of the concrete made with PPC compared to that of concrete made with OPC could be due to the same reasons stated for the difference in the water demand of the two types of concrete.
7. The use of PPC resulted in lower chloride-ion penetrability at 28 days; at 91 days, the improvement was insignificant, especially for higher grades of concrete.

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Table 1 - Physical Properties and Chemical Analysis of the Cements and Fly Ash

	Ordinary Portland Cement (OPC)	Portland Pozzolana Cement (PPC)	Garden Reach Fly Ash
Physical Tests			
Specific gravity	3.17	3.12	2.03
Fineness			
-passing 45 micron	84	92	88
-specific surface, Blaine, cm^2/g	3294	3402	4892
Compressive strength of 70.7 mm cubes, Mpa			
3-day	30.12	27.91	-
7-day	37.22	37.49	-
28-day	42.83	47.44	-
Chemical Analysis (%)			
Silicon dioxide (SiO_2)	18.67	-	57.1
Aluminium oxide (AI_2O_3)	6.07	-	27.1
Ferric oxide (Fe_2O_3)	4.96	-	7.4
Calcium oxide (CaO)	60.12	-	2.1
Magnesium oxide (MgO)	2.13	2.93	1.2
Alkalis equivalent	-	-	2.42
Titanium oxide (TiO_2)	-	-	1.2
Sulphur trioxide (SO_3)	2.57	2.68	0.1
Loss on ignition	1.98	1.95	1.3
Bogue Potential Compound Composition			
Tricalcium silicate C_3S	47.6	-	-
Dicalcium silicate C_2S	17.9	-	-
Tricalcium aluminate C_3A	7.7	-	-
Tretracalcium aluminoferrite C_4AF	15.1	-	-

Table 2 - Grading of Coarse and Fine Aggregate

Coarse Aggregate			Indian Standard Requirements for Coarse Aggregate As per IS 383		Fine Aggregate		Indian Standard Requirements for Fine Aggregate As per IS 383
Sieve Size, mm	Type I Passing, %	Type II Passing, %	Type I (20mm graded)	Type II (16mm graded)	Sieve Size, mm	Passing, %	Passing, % (For Grading Zone II)
20.00	100.00	100.00	95-100	100	4.75	100.0	90-100
16.00	90.00	100.00	-	90-100	2.36	95.7	75-100
12.50	-	-	-	-	1.18	82.2	55-90
10.00	50.00	51.54	25-55	30-70	0.60	55.1	35-59
4.75	2.12	0.00	0-10	0-10	0.30	12.6	0-30
2.36	-	-	-	-	0.15	0.9	0-10

Table 3 – Mixture proportions and properties of fresh concrete of grade M20 concrete made with OPC and different percentages of fly ash

Mix. No.	W/CM	Water, kg/m^3	Cement,		Fly Ash		Coarse Agg, kg/m^3	Fine Agg. kg/m^3	W.R.,* L/m^3	Ambiant Temp., °C	Temp of Fresh Concrete, °C	Unit Weight, kg/m^3	Slump,	
			%	kg/m^3	%	kg/m^3							Initial	After 30 min.
1	0.50	174	100	348	0	0	1206	739	3.0	27.0	28.0	2465	75	40
2	0.48	165	70	241	30	103	1200	735	1.8	26.0	27.0	2445	105	70
3	0.46	162	60	212	40	141	1233	755	3.1	25.5	27.0	2505	105	50
4	0.43	149	50	174	50	174	1208	739	3.8	26.0	26.0	2445	95	90

* Water-reducing admixture

Table 4 – Mixture proportions and properties of fresh concrete of grade M40 concrete made with OPC and different percentages of fly ash

Mix. No.	W/CM	Water, kg/m^3	Cement,		Fly Ash		Coarse Agg, kg/m^3	Fine Agg. kg/m^3	SP,* L/m^3	Ambiant Temp., °C	Temp of Fresh Concrete, °C	Unit Weight, kg/m^3	Slump,	
			%	kg/m^3	%	kg/m^3							Initial	After 30 min.
5	0.40	152	100	379	0	0	1117	759	5.5	29.5	31.0	2405	120	65
6	0.36	139	70	271	30	116	1144	773	4.9	30.0	31.0	2445	110	60
7	0.34	132	60	233	40	155	1148	775	4.6	30.0	31.0	2445	105	40
8	0.32	126	50	197	50	197	1168	789	4.6	30.0	31.0	2480	120	70
9	0.32	125	45	176	55	215	1148	779	4.9	30.0	31.0	2445	150	80

* Superplasticizer

Table 5 – Mixture proportions and properties of fresh concrete of grade M60 concrete made with OPC and different percentages of fly ash

Mix. No.	W/CM	Water, kg/m^3	Cement,		Fly Ash		Coarse Agg, kg/m^3	Fine Agg. kg/m^3	SP,* L/m^3	Ambiant Temp., °C	Temp of Fresh Concrete, °C	Unit Weight, kg/m^3	Slump,	
			%	kg/m^3	%	kg/m^3							Initial	After 30 min.
10	0.32	147	100	461	0	0	1148	687	9.6	28.5	30.0	2445	105	80
11	0.29	136	70	328	30	140	1166	698	5.9	30.0	31.0	2465	95	60
12	0.29	135	60	279	40	186	1160	695	7.8	29.5	30.5	2455	100	60
13	0.28	130	50	231	50	231	1157	694	6.2	29.0	30.0	2445	115	50

* Superplasticizer

Table 6 – Mixture proportions and properties of fresh concrete of grade M20 concrete made with PPC and different percentages of fly ash

Mix. No.	W/CM	Water, kg/m^3	Cement,		Fly Ash		Fly Ash* In total CM, %	Coarse Agg., kg/m^3	Fine Agg. kg/m^3	SP,** L/m^3	Ambiant Temp., °C	Temp of Fresh Concrete, °C	Unit Weight, kg/m^3	Slump,	
			%	kg/m^3	%	kg/m^3								Initial	After 30 min.
14	0.52	172	100	332	0	0	30	1158	709	3.6	26.0	27.0	2370	80	45
15	0.48	164	86	293	14	48	40	1187	727	2.7	26.0	27.0	2420	95	60
16	0.46	158	71	244	29	99	50	1190	729	3.7	24.5	27.0	2420	110	65

* Based on the assumption that the PPC contains 30% of fly ash
** Superplasticizer

Table 7 – Mixture proportions and properties of fresh concrete of grade M40 concrete made with PPC and different percentages of fly ash

Mix. No.	W/CM	Water, kg/m^3	Cement,		Fly Ash		Fly Ash* In total CM, %	Coarse Agg., kg/m^3	Fine Agg. kg/m^3	SP,** L/m^3	Ambiant Temp., °C	Temp of Fresh Concrete, °C	Unit Weight, kg/m^3	Slump,	
			%	kg/m^3	%	kg/m^3								Initial	After 30 min.
17	0.42	160	100	383	0	0	30	1134	765	6.8	30.0	31.5	2445	95	30
18	0.38	146	86	329	14	54	40	1136	767	5.7	31.0	32.5	2430	125	65
19	0.36	138	71	273	29	110	50	1133	766	5.5	30.0	31.0	2420	115	55
20	0.32	126	64	253	36	142	55	1166	792	5.8	24.5	27.0	2480	95	60

* Based on the assumption that the PPC contains 30% of fly ash

** Superplasticizer

Table 8 – Mixture proportions and properties of fresh concrete of grade M60 concrete made with PPC and different percentages of fly ash

Mix. No.	W/CM	Water, kg/m^3	Cement,		Fly Ash		Fly Ash* In total CM, %	Coarse Agg., kg/m^3	Fine Agg. kg/m^3	SP,** L/m^3	Ambiant Temp., °C	Temp of Fresh Concrete, °C	Unit Weight, kg/m^3	Slump,	
			%	kg/m^3	%	kg/m^3								Initial	After 30 min.
21	0.34	157	100	461	0	0	30	1149	688	9.7	28.0	30.0	2455	85	45
22	0.32	147	86	397	14	64	40	1148	687	5.8	28.0	29.5	2445	110	35
23	0.30	139	71	328	29	135	50	1159	694	6.4	27.0	28.0	2455	110	45

* Based on the assumption that the PPC contains 30% of fly ash

** Superplasticizer

Table 9 - Compressive Strength of grade M20 concrete made with OPC and different percentages of fly ash

Mix No.	Cement, %	Fly Ash %	Fly ash in total CM, %	W/CM	Compressive Strength, MPa					
					1 day	3 days	7 days	28 days	56 days	91days
1	100	0	0	0.50	13.3	31.1	38.6	40.7	52.0	45.3
2	70	30	30	0.48	7.6	17.0	26.1	45.7	50.0	53.9
3	60	40	40	0.46	-	15.3	23.6	44.1	59.5	54.7
4	50	50	50	0.43	-	14.1	21.5	38.1	42.8	40.5

Table 10 - Splitting tensile and flexural strengths, and chloride-ion penetrability test results of grade M20 concrete made with OPC and different percentages of fly ash

Mix. No.	Cement, %	Fly Ash, %	Fly ash in total CM, %	W/CM	Splitting Tensile Strength MPa		Flexural Strength MPa		Chloride-ion Penetrability, coulombs	
					28 days	91 days	28 days	91 days	28 days	91 days
1	100	0	0	0.50	3.6	4.0	5.2	5.2	5290	3110
2	70	30	30	0.48	3.4	3.9	5.5	5.6	1570	530
3	60	40	40	0.46	3.5	4.3	5.6	7.9	1450	500
4	50	50	50	0.43	2.6	3.9	4.5	6.0	1800	630

Table 11 - Compressive Strength of grade M40 concrete made with OPC and different percentages of fly ash

Mix No.	Cement, %	Fly Ash %	Fly ash in total CM, %	W/CM	Compressive Strength, MPa					
					1 day	3 days	7 days	28 days	56 days	91days
5	100	0	0	0.40	20.1	36.0	42.1	48.8	50.8	52.9
6	70	30	30	0.36	11.5	32.7	34.3	54.9	65.8	73.2
7	60	40	40	0.34	13.0	30.6	38.6	58.9	67.5	73.6
8	50	50	50	0.32	4.6	25.4	38.1	50.4	52.5	57.7
9	45	55	55	0.32	7.8	23.3	29.7	49.6	52.7	54.3

Table 12 - Splitting tensile and flexural strengths, and chloride-ion penetrability test results of grade M40 concrete with OPC and different percentages of fly ash

Mix. No.	Cement, %	Fly Ash, %	Fly ash in total CM, %	W/CM	Splitting Tensile Strength MPa		Flexural Strength MPa		Chloride-ion Penetrability, coulombs	
					28 days	91 days	28 days	91 days	28 days	91 days
5	100	0	0	0.40	3.5	3.7	5.3	6.8	1860	1360
6	70	30	30	0.36	3.7	3.8	5.5	7.4	1460	250
7	60	40	40	0.34	4.3	4.9	6.5	7.5	1240	230
8	50	50	50	0.32	3.9	5.1	5.9	7.3	1000	260
9	45	55	55	0.32	3.7	4.4	4.8	5.8	890	330

Table 13 - Compressive Strength of grade M60 concrete made with OPC and different percentages of fly ash

Mix No.	Cement, %	Fly Ash %	Fly ash in total CM, %	W/CM	Compressive Strength, MPa					
					1 day	3 days	7 days	28 days	56 days	91days
10	100	0	0	0.32	34.2	41.8	52.7	60.6	61.6	61.9
11	70	30	30	0.29	18.8	39.0	43.7	68.1	79.1	80.2
12	60	40	40	0.29	12.8	30.7	42.2	60.3	70.0	72.3
13	50	50	50	0.28	6.7	29.2	37.9	70.2	68.8	71.6

Table 14 - Splitting tensile and flexural strengths, and chloride-ion penetrability test results of grade M60 concrete made with OPC and different percentages of fly ash

Mix. No.	Cement, %	Fly Ash, %	Fly ash in total CM, %	W/CM	Splitting Tensile Strength MPa		Flexural Strength MPa		Chloride-ion Penetrability, coulombs	
					28 days	91 days	28 days	91 days	28 days	91 days
10	100	0	0	0.32	4.1	5.6	7.5	8.7	1970	960
11	70	30	30	0.29	4.6	4.8	8.8	9.4	530	170
12	60	40	40	0.29	4.4	3.5	6.7	7.8	610	200
13	50	50	50	0.28	3.7	4.0	7.0	6.9	1140	270

Table 15 - Compressive Strength of grade M20 concrete made with PPC and different percentages of fly ash

Mix No.	Cement, %	Fly Ash %	Fly ash* in total CM, %	W/CM	Compressive Strength, MPa					
					1 day	3 days	7 days	28 days	56 days	91days
14	100	0	30	0.52	9.5	21.6	27.9	40.2	48.6	51.2
15	86	14	40	0.48	2.2	18.1	26.3	40.2	49.7	55.3
16	71	29	50	0.46	1.1	17.9	21.9	40.7	51.0	49.0

* Based on the assumption that the PPC contains 30% fly ash.

Table 16 - Splitting tensile and flexural strengths, and chloride-ion penetrability test results of grade M20 concrete made with PPC and different percentages of fly ash

Mix. No.	Cement, %	Fly Ash, %	Fly ash in* total CM, %	W/CM	Splitting Tensile Strength MPa		Flexural Strength MPa		Chloride-ion Penetrability, coulombs	
					28 days	91 days	28 days	91 days	28 days	91 days
14	100	0	30	0.52	3.6	4.5	4.9	6.5	1430	540
15	86	14	40	0.48	3.5	4.4	5.7	7.1	940	350
16	71	29	50	0.46	2.6	3.6	5.8	7.0	1170	340

* Based on the assumption that the PPC contains 30% fly ash.

Table 17 - Compressive Strength of grade M40 concrete made with PPC and different percentages of fly ash

Mix No.	Cement, %	Fly Ash %	Fly ash* in total CM, %	W/CM	Compressive Strength, MPa					
					1 day	3 days	7 days	28 days	56 days	91days
17	100	0	30	0.42	20.8	31.9	37.6	46.2	48.1	57.4
18	86	14	40	0.38	19.0	29.8	37.8	52.4	52.2	61.3
19	71	29	50	036	11.6	26.6	34.0	51.0	56.8	60.3
20	64	36	55	0.32	12.2	28.7	31.6	52.9	59.6	55.7

* Based on the assumption that the PPC contains 30% fly ash

Table 18 - Splitting tensile and flexural strengths, and chloride-ion penetrability test results of Grade M40 concrete made with PPC and different percentages of fly ash

Mix. No.	Cement, %	Fly Ash, %	Fly ash in* total CM, %	W/CM	Splitting Tensile Strength MPa		Flexural Strength MPa		Chloride-ion Penetrability, coulombs	
					28 days	91 days	28 days	91 days	28 days	91 days
17	100	0	30	0.42	3.7	4.5	5.3	6.5	1810	360
18	86	14	40	0.38	4.3	3.4	6.5	8.9	840	310
19	71	29	50	036	4.6	3.7	5.6	8.0	870	270
20	64	36	55	0.32	3.9	n.a.	n.a.	n.a.	n.a.	n.a.

* Based on the assumption that the PPC contains 30% fly ash

Table 19 - Compressive Strength of grade M60 concrete made with PPC and different percentages of fly ash

Mix No.	Cement, %	Fly Ash %	Fly ash* in total CM, %	W/CM	Compressive Strength, MPa					
					1 day	3 days	7 days	28 days	56 days	91days
21	100	0	30	0.34	23.7	35.9	43.5	65.9	65.4	67.8
22	86	14	40	0.32	18.7	32.6	41.6	62.1	66.2	69.3
23	71	29	50	0.30	20.6	32.3	45.0	52.1	73.3	69.8

* Based on the assumption that the PPC contains 30% fly ash.

Table 20 - Splitting tensile and flexural strengths, and chloride-ion penetrability test results of grade M60 concrete made with PPC and different percentages of fly ash

Mix. No.	Cement, %	Fly Ash, %	Fly ash in* total CM, %	W/CM	Splitting Tensile Strength MPa		Flexural Strength MPa		Chloride-ion Penetrability, coulombs	
					28 days	91 days	28 days	91 days	28 days	91 days
21	100	0	30	0.34	4.9	5.1	7.3	7.7	910	330
22	86	14	40	0.32	5.2	5.6	7.3	7.3	570	220
23	71	29	50	0.30	4.0	5.9	7.8	7.0	630	220

* Based on the assumption that the PPC contains 30% fly ash.