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Evaluation of the technical and economical aspects of using type CEM III cements in concrete

Researchers at Adana Çimento in Turkey have undertaken a thorough investigation into the relative strengths of concretes made with normal Portland cement (CEM I) compares to those derived from GGBFS-based cements (CEM III). The results of this investigation are presented in this paper, with the central conclusion being that concretes made with cements containing up to 65% by weight of GGBFS, have improved strength, lower unit costs and a more benign environmental footprint compared with concretes made from CEM I cements.

Cements containing ground granulated blast furnace slag (GGBFS) are usually manufactured in cement plants close to steel mills and are commonly used all over the world. Such cements contribute effectively to the high durability of concretes having good strength and water tightness. This paper summarises and compares the results of tests conducted on concretes containing local cements produced at Adana Cement Co.

Concretes made with CEM III/A 42.5 N type cement were compared with those obtained with CEM II/B-S 42.5 R and CEM I 42.5 R types of cement. The comparisons involved 2, 7, 28 day-compressive strengths, water requirement, chloride and water penetration properties. In addition, similar tests were performed on self compacting concretes (SCC) produced with the same cements.

According to the results, concretes made with CEM III/A 42.5 N cement had comparable 28 day strengths with concretes containing the other two cements. CEM III/A 42.5 N concretes were more resistant to water and chloride penetration and more economical based on unit strength. As well as containing less clinker, they are 'environmentally friendly'.

Introduction

The addition of GGBFS either in cement or in concrete improves the following properties of concrete related to its durability as explained in various publications:[1-4]

Sulphate resistance: Cements with added GGBFS contain less alumina, $Ca(OH)_2$ and C3A compared with normal Portland cement and they also have less water demand. This results in a more impermeable cement paste for penetration of sulphate ions and provides conditions to prevent ettrengite formation. Around 65% or more slag addition makes the cement comparable to sulphate resisting cement.

Resistance to chlorides: The permeability of concrete decreases due to fine GGBFS particles and their hydration products in the cement paste. Such cement pastes also absorb more chloride ions. It has been determined that, compared with normal Portland cement pastes, slag cement pastes are 100 times less permeable against potassium ions.

Alkali-silica reaction: The use of at least 50% GGBFS in cement is effective in reducing alkali-silica reaction expansions.

Acid resistance: Concretes containing GGBFS have been found to be more resistant to diluted acids compared with those containing normal Portland or sulphate resistant cements.

Resistance to sea water: Concrete in sea water is subjected to sulphates and chlorides. Field studies in Belgium, Germany, Norway, England and France have been conducted on the performance of concrete structures built with different types of cement in sea water. There was less spalling and reinforcement corrosion in concretes built with slag cements (25-35% GGBFS). Slag cements with more than 50% GGBFS performed even better.

Reinforcement corrosion: Highly alkaline cement pastes protect embedded steel bars against corrosion. Carbonation or penetration of chloride ions into concrete can initiate corrosion. Cement pastes made with slag cements can effectively block the entrance of chloride ions and prolong the useful life of concrete structures.

Thermal behaviour and cracking: The hydration of cement is an exothermic process. The heat produced can cause temperature gradients and cracking in massive structures and can also be harmful in rich concrete mixes, in rapid curing and in hot weather concreting. In slag cements, the heat producing components of clinker is partially replaced with GGBFS and heat of hydration is effectively reduced. Thus, adverse conditions mentioned above that would otherwise serve to harm the durability of concrete do not take place.

In Turkey there are three main steel works, located in Ereğli (Erdemir) Karabük (Kardemir) and İskenderun (İsdemir). The total granulated slag obtained from these three steel works currently stands at about 1.5Mt/y. İsdemir, located close to the plants of Adana Cement Company, currently produces 630,000t of granulated slag per annum, and its output is expected to reach 900,000t in 2008. The Adana Cement İskenderun plant uses granulated slag obtained from the İskenderun steel works to produce slag cements CEM II/B-S 42.5R and CEM III/A 42.5R according to Turkish cement standard TS EN 197-1. Currently, about 17Mt of slag-containing cements (CEM II, III and V) are produced annually in Turkey.

A comprehensive study was initiated by OYAK Group Adana Cement Co in collaboration with Turkish Cement Manufacturers' Association (TÇMA) to confirm some of the technical advantages of slag cements mentioned above using local materials, and also to make comparative economic assessments. This paper presents some of the findings of that study.

Experimental work: Materials

Cements

The cements used in the study were produced by Adana Cement Co. They were: Portland Cement CEM I 42.5 R, Portland Slag Cement CEM II/B-S 42.5 R (containing around 33.5% mineral admixture) and blast furnace slag cement CEM III/A 42.5 N (containing around 55.5% mineral admixture). The other properties of these cements are given in Table 1.

Chemical admixtures

Different types of water-reducing chemical admixtures were used in the concrete mixtures, depending on the type of cement. A naphthalene sulfonate-based superplasticiser, which showed good performance with slag cements, was used with CEM III/A 42.5 N. Another superplasticiser was used with the other two cements. For self compacting concrete a synthetic polymer-based hyperplasticiser was chosen.

Aggregate

Crushed stone aggregate was used in the concrete mixtures. For normal mixtures the aggregate was composed from four size groups with a maximum particle size of 22mm as shown below:

- 0.27 (0-2mm);
- 0.22 (0-4mm);
- 0.25 (4-15mm);
- 0.26 (15-22mm).

For the self compacting concrete the maximum particle size was 15mm. The combinations from three size groups were as follows:

- 0.24 (0-2mm);
- 0.36 (0-4mm);
- 0.40 (4-15mm).

Some physical properties of the aggregate are shown in Table 2.

Laboratory Tests

Concrete mixtures

Normal concrete mixtures were prepared using the three types of cement and five levels of cement content: 270, 280, 290, 300, 310 kgm^{-3} for each of them. The chemical admixture dosages were 1.2% by weight of cement. The workability of the mixtures was kept constant at 21cm slump. Material quantities for the 15 concrete mixtures are given in Table 3.

For the self-compacting concrete, two mixtures were prepared. In one, CEM I 42.5R type cement was used at 500 kgm^{-3} and in the other CEM III/A 42.5 N type of cement was used at 450kgm^{-3}. The water/cement ratio was 0.40 and hyperplasticiser dosage was again 1.2% by weight of cement in both mixtures. The material quantities are shown in Table 4.

Properties	CEM I 42.5R	CEM II/B-S 42.5R	CEM III/A 42.5N
Insoluble residues (%)	0.24	0.50	0.38
SO_3 (%)	2.56	2.47	1.83
MgO	1.68	3.48	4.22
Loss on ignition (%)	2.85	2.08	2.25
Specific gravity (g/cm^3)	3.10	3.02	2.97
Specific surface (cm^2/g)	3230	4660	4690

Table 1: Properties of cement.

Aggregate type	Specific gravity (gcm^{-3})	Water absorption capacity (%)
Crushed stone 0-2mm	2.65	2.20
Crushed stone 0-4mm	2.65	2.20
Fine aggregate 4-15mm	2.68	1.40
Coarse aggregate 15-22mm	2.70	1.20

Table 2: Properties of the aggregate.

Mixture No.	Cement type	Water-to-cement ratio	Cement quantity (kgm^{-3})	Fine aggregates (kgm^{-3})	Coarse aggregates (kgm^{-3})	Chemical admixtures (kgm^{-3})
1	CEM I 42.5R	0.74	270	920	957	3.24
2	CEM I 42.5R	0.71	280	917	954	3.36
3	CEM I 42.5R	0.68	290	915	952	3.48
4	CEM I 42.5R	0.66	300	909	946	3.60
5	CEM I 42.5R	0.64	310	904	941	3.72
6	CEM II/BS 42.5R	0.74	270	920	957	3.24
7	CEM II/BS 42.5R	0.71	280	917	954	3.36
8	CEM II/BS 42.5R	0.68	290	915	952	3.48
9	CEM II/BS 42.5R	0.66	300	909	946	3.60
10	CEM II/BS 42.5R	0.64	310	904	941	3.72
11	CEM III/A 42.5N	0.72	270	927	965	3.24
12	CEM III/A 42.5N	0.69	280	924	961	3.36
13	CEM III/A 42.5N	0.67	290	918	955	3.48
14	CEM III/A 42.5N	0.65	300	913	950	3.60
15	CEM III/A 42.5N	0.62	310	913	949	3.72

Table 3: Material quantities in normal concrete mixtures.

Test procedures and results

The compressive strengths of all concrete mixtures were determined at 2, 7 and 28 days according to TS EN 12390-3 standard.[5] Chloride and water penetration tests were performed on normal 28-day concrete mixtures with 300kgm^{-3} cement content and on self-compacting concrete mixtures.

Mixture No.	Cement type	Water-to-cement ratio	Cement quantity (kgm^{-3})	Crushed sand (kgm^{-3})	Crushed gravel (kgm^{-3})	Plasticiser chemical additive (kgm^{-3})	Flow (cm)
16	CEM I 42.5R	0.40	500	1001	668	6.0	65
17	CEM III/A 42.5N	0.40	450	1061	707	5.4	71

Table 4: Material quantities in self-compacting concrete mixtures.

Mixture No.	Strength (MPa)			Chloride penetration (Coulombs)	Water penetraton (mm)
	2 days	7 days	28 days		
1	12.9	18.7	25.3		
2	14.2	19.7	27.7		
3	14.9	21.5	28.0		
4	**17.2**	**22.6**	**28.5**	**>15,000**	**99**
5	17.3	24.4	21.6		
6	9.5	17.8	27.4		
7	9.7	18.2	28.5		
8	10.3	18.6	29.3		
9	**10.5**	**19.5**	**30.0**	**9392**	**53**
10	10.7	22.8	33.5		
11	8.4	16.7	26.1		
12	9.4	17/0	26.9		
13	9.5	18.3	27.4		
14	**9.7**	**18.8**	**29.4**	**2237**	**36**
15	10.3	19.4	32.2		

Table 5: Test results for normal concrete mixtures.

The standard test to determine concrete's ability to resist chloride penetration (ASTM C1202) involves measuring the electrical current passing through a saturated concrete specimen placed between 3% NaCl and 0.3moldm^{-3} NaOH cells. The amount of current was measured at 30min intervals for a total of 6 hours and plotted. The area under the curve was calculated as the total amount of current in coulombs.[6]

Mixture No.	Strength (MPa)			Chloride penetration (Coulombs)	Water penetraton (mm)
	2 days	7 days	28 days		
16	32.6	42.8	51.0	7872	52
17	16.7	38.9	53.5	707	24

Table 6: Test results for self-compacting concrete mixtures.

Mixture No.	Raw material cost (YTLm^{-3})	28 days compressive strength (MPa)	Price for 1Mpa (YTL)
4	50.95	28.5	1.79
9	48.25	30.0	1.61
14	46.91	29.4	1.60

Table 7: costs of normal concrete mixtures per unit strength.

The depth of penetration of water under pressure into concrete was determined according to TS EN 12390-8 standard. Oven-dried concrete specimens were subjected to water pressure for 48 hours under 1atm, 24 hours under 3atm and 24 hours under 7atm. Afterwards, specimens were split and depths of water penetration were measured.[7] The test results for normal and self-compacting concrete mixtures are listed in Tables 5 and 6, respectively.

Mixture No.	Cement quantity	Raw material cost (YTLm^{-3})	28 days compressive strength (MPa)	Price for 1Mpa (YTL)
16	500	84.63	51.0	1.66
17	450	70.57	53.5	1.32

Table 8: Costs of self-compacting concrete mixtures per unit strength.

Discussion

Compressive strength

The results of the compressive strength tests listed in Table 5 indicates that at early ages (days 2 and 7), concretes made with CEM I 42.5 R cement had higher strengths than the the concretes made with CEM II/B-S 42.5 R and CEM III/A 42.5 N cements for all water/cement ratios. However, the strengths at 28 days of both concretes containing the slag cements exceeded the strengths of CEM I concrete. At 28 days, concretes made with CEM III/A 42.5 N cement almost reached CEM II/B-S 42.5 R concrete values while exceeding the strengths of CEM I 42.5 R concrete. The delay in strength gain of concretes containing slag cements are attributed to the delayed hydration of blast furnace slag. Slag cement concretes also showed faster strength gain from 2nd to 7th days compared with CEM I concrete.

Similar comments could be made for self compacting concretes studying the strength values in Table 6. Again the strengths of concretes made with CEM III/A 42.5 N cement remained below the strengths of CEM I 42.5 R concrete at days 2 and 7, but exceeded them at 28 days.

Chloride penetration

As seen from Tables 5 and 6, the ability to resist chloride penetration of concretes improved dramatically with the use of slag cements. CEM III/A 42.5 N cement was the most effective in this respect. This could be explained by the formation of the additional pozzolanic gel in slag cement pastes, which serves to close the pores and increase the fineness of the slag cements.

Water penetration

Water penetration depths in Tables 5 and 6 indicate that using slag cements improved the resistance of concretes to the penetration of water under pressure. Again, CEM III / A 42.5 N cement was the most effective and the results could be explained in the same terms as for the penetration of chloride ions.

Cost comparisons for concrete

In Table 7, raw material costs per unit volume of the normal concrete mixtures having 300 kgm^{-3} cement content are shown, as well as their 28 day compressive strengths, which are close to each other. In the last column, costs (in Turkish Lira, YTL) per unit strength (1MPa) are calculated (1YTL = US$0.85/Euro0.59. It can be seen that using slag cements (mixtures 9 and 11) can lower the cost of concrete by about 11% as compared with the cost of CEM I cement concrete (mixture 4).

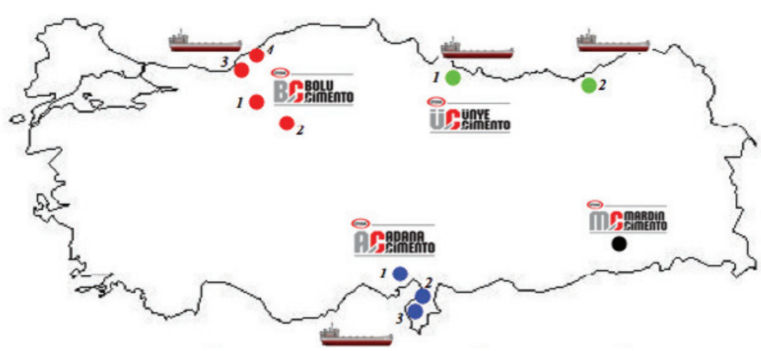
Table 8 contains similar information for self-compacting concrete mixtures. This time, the cost of concrete made with CEM I 42.5 R cement (mixture 16) is reduced by about 21% by using CEM III/A 42.5 N ce-

Mixture No.	Cement type	Quantity (kgm^{-3})	Amount of clinker used in cement (%)	Clinker quantity (kgm^{-3})	Difference with CEM III
4	CEM I 42.5R	300	97.0	291.0	157.5
9	CEM II/BS 42.5R	300	66.5	199.5	66.0
14	**CEM III/A 42.5N**	**300**	**44.5**	**133.5**	**–**
16	CEM I 42.5R	500	97.0	485.0	285.5
17	**CEM III/A 42.5N**	**450**	**44.5**	**44.5**	**–**

Table 9: Clinker quantity according to cement types and comparison with CEM III.

ment (mixture 17) on unit strength basis. It should be mentioned that in mixture 17, while obtaining higher strength at and beyond 28 days, 50kg less of cement was used per cubic metre of concrete. A larger flow value was also obtained.

The clinker percentages of the three cements used in this study and the clinker contents per cubic metre of normal concretes with 300kgm^{-3} cement content and self compacting concretes are listed in Table 9. It can be seen that by using CEM III/A 42.5 N cement instead of the other two cements, 66-157.5kg of clinker is saved per cubic metre of normal concrete mixtures. The saving in clinker content is 285kgm^{-3} for self-compacting concrete mixtures.



Below: Oyak Cement Group factories in Turkey, with colour-coded key to plants and offices.

Adana Çimento
1 - Headquarters
2 - İskenderun 1
3 - İskenderun 2 (operational in 2008)

Bolu Çimento
1 - Headquarters
2 - Ankara
3 - Ereğli (opened in 2007
4 - Ereğli (operational in 2009)

Ünye Cimento
1 - Headquarters
2 - Çayeli

Mardin Çimento

Conclusions

The main results of the study could be summarised as follows: Concretes made with slag cements have lower 2nd and 7th day strengths compared with the ones made with CEM I cement. However, they gained strength faster afterwards and reached or exceeded the strength of CEM I cement concrete by 28 days. Concretes made with CEM III/A 42.5 N cement, which had a slag content of around 55.5%, almost reached the strength of concretes made with CEM II/B-S 42.5 R cement, having around 33.5% slag, and exceeded the strength of concretes made with CEM I 42.5 R cement at 28 days.

Using slag cements instead of CEM I cement improves the resistance to water and chloride penetration of concrete and contributes to its durability. In this respect CEM III/A 42.5 R cement was the most effective.

Using slag cements and especially CEM III/A 42.5 N in self-compacting concrete mixtures again resulted in comparable or slightly higher 28 day strengths, improved water and chloride resistances and better flow characteristics, as compared with using CEM I 42.5 R cement.

An 11% reduction in the cost of concrete per 1MPa of strength was observed upon using a CEM III/A 42.5 N cement. This was achieved with a cement content of 300 kgm^{-3} at 28-days strength. This equated to a saving of 157.5kgm^{-3} in clinker content as compared to using CEM I 42.5 R cement. A higher cost reduction, around 21%, and a reduction in clinker content of 285 kgm^{-3} was possible in self-compacting concrete mixtures.

It can be concluded that concretes made with CEM III/A cements, which can contain up to 65% GGBFS, have improved strength and durability properties and lower unit costs as compared with CEM I cement concretes. Moreover, CEM III cements are also 'environmentally friendly' as they make use of the main by-product of the steel industry. Their reduced clinker content means savings in natural raw materials and fuels and reduced CO_2 emissions since the production of 1t of clinker results in the emission of almost 1t of CO_2 into the atmosphere.

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