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Chemical Composition of Cements Produced in Saudi Arabia and Its Influence on Concrete Strength

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Abstract. The current cement consumption in the Kingdom exceeds 25 million tons per year, which is one of the highest per capita consumption in the world. Presently, there are eight cement companies operating in the Kingdom with a total production capacity of about 22 million tons per year. However, in the Kingdom there is a plan for new plants and major expansion of existing plants which is expected to double the current production of cement in the coming years.

In this research project, the variability of chemical composition of cements produced in the Kingdom and its impact on the strength development of concrete up to 5 years were investigated. The test results showed that the chemical composition of Type I cement produced in the Kingdom is similar to typical values of Type I cement in the literature. However, the Type V cement demonstrated high C_3S and low C_2S contents. It was also found that all cements have low amount of alkali equivalent which can be classified according to ASTM C150 as low-alkali cement. The results of compressive strength of concrete made with Type I cement were 2-4 MPa higher than corresponding concrete made with Type V cement at all ages up to 5 years.

Introduction

Portland cement concrete is the dominant construction material in the Kingdom of Saudi Arabia and other countries in the Middle East. The first cement factory in the Kingdom was established in Jeddah in 1959 with a production capacity of 100,000 tons per year. The number of cement factories increased gradually and cement production reached about 700,000 tons per year in 1970. Cement production vs. consumption in the Kingdom during the periods 1970-2005 is shown in Fig. 1. The cement consumption reached the highest level during the construction boom of the mid-seventies; the total cement consumption reached about 12.9 million tons in 1980, while the production was only 2.9 million tons. The cement consumption continued to increase until 1983 when it touched 24 million tons then decreased gradually till it reached about 10.9 million tons in 1990. In the mean time, cement production continued to grow steadily and became almost equal with its consumption in 1990. To meet the consumption demand, the Kingdom has imported around 10-15 million tons of cement per year early 1980's. In the last 15 years, both production and consumption grew steadily reaching 22 million tons per year, which is one of the highest per capita consumption in the world (Alhozaimy, 1999; Tuncalp, 1990). There are now eight cement factories geographically spread all over the Kingdom with a total production capacity of 22 million tons per year in 2005. Most cement factories produce only Type I and Type V cement. Currently, there are new plants and major expansion of existing plants. It is expected that the cement production in the Kingdom will reach 45 million tons per year in the coming years.

The quality of cement is vital for the production of good concrete. The manufacturing of cement requires stringent control and conformance to the approved standards and specifications. The properties

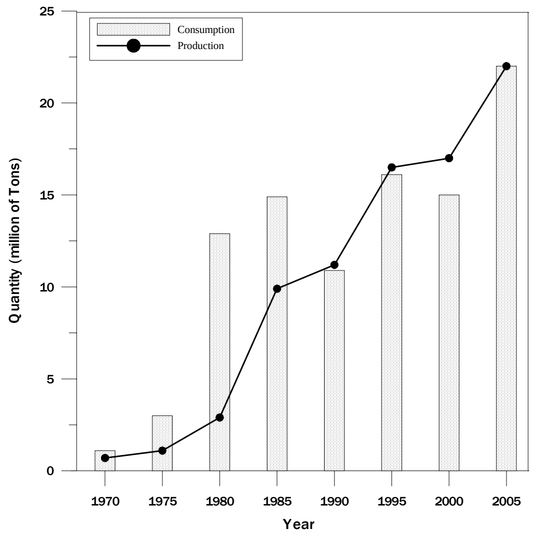

Fig. 1. Cement production vs. consumption.

of local cement comply with international standards. However, the variability of physical and chemical properties of cement from these factories is not well documented. The issue of strength development of concrete made with locally cement and its variation with existing literature has not been addressed.

This paper presents the results of an experimental program conducted to examine both chemical and physical properties of local cement. Cement samples for both Type I and Type V used in this study were obtained from four cement factories in the Kingdom. These samples were also used to study the strength development of concrete made using local cement and to establish the ratio of 7-day to 28-day strength of concrete.

2. Experimental Program

The experimental program was designed to investigate the cement properties and the effect of local cement types and sources on the strength development of concrete. Cement samples for both Type I and Type V were collected from four factories. In addition, data-sheet showing the chemical and physical properties of each type of cement were obtained from factories. X-ray fluorescence analysis (XRF) was conducted on each cement to determine the elemental compositions of cement form the various sources. In addition, eight laboratory mixes were prepared using the two cement types from the four sources. For each mix, a total of 32 cubes (150 x 150 x 150 mm) were prepared and cured in lime-saturated water in the laboratory until the testing age. Compressive strength testing was performed at the age of 3, 7, 28, 90, 180 days, 1, 2 and 5 years.

3. Material and Mix Proportions

The cement used was Type I and Type V obtained for this study. Coarse aggregates were a blend of crushed limestone with aggregate sizes of 20 mm and 10 mm. The specific gravity based on saturated and surface dry condition (SSD) of 20-mm coarse aggregate was 2.65, and its absorption capacity was 1.69%, while the specific gravity of 10-mm coarse aggregate was 2.7, and its absorption capacity was 1.94%. The fine aggregate with absorption capacity of 1.2% was used. The gradation of coarse and fine aggregates met the ASTM C33 requirements. The mix proportions used in this investigation are shown below:

Cement	350 kg/m^3
Water	192.5 kg/ m^3
20 mm Agg.	730 kg/m^3
10 mm Agg.	390 kg/m^3
Sand	715 kg/m^3

4. Mixing and Curing Procedures

Specimens for the compressive strength were cast from eight separate batches. Each batch was mixed in a concrete mixer of 0.4 cubic meter capacity. The mixing procedures followed basically ASTM C192. After mixing, the concrete temperature and slump tests were performed for each batch according to ASTM C1064 and ASTM C143, respectively. The initial concrete temperatures of all mixes were in the range of 17–20^{o}C. The effect of cement source and type on the workability of concrete was limited with slump values of all eight batches being in the range of 125 ± 15 mm.

Cube specimens (150 x 150 x 150 mm) were cast in steel molds according to BS 1881 Part 116. The cube specimens were consolidated by external vibration in two layers. After casting, the specimens were covered with wet burlap and plastic sheets for 24 hours. After demolding, the specimens were cured in lime saturated water at a temperature of 21 ± 2 ^{o}C until the testing age.

5. Results and Discussion

5.1. Chemical composition

In the Kingdom, all cement factories produce cement in accordance with ASTM C150. Independent chemical analysis of cement samples for the purpose of comparison with test data provided by the cement factories was performed; the results are shown in Table 1. The results of the chemical analysis are similar to the values provided by cement factories in their test certificates. The difference was very limited within the range of 0 to 1% except for CaO and loss on ignition values, which differed by up to 2%. These results confirm that the results provided by the cement factories in the test certificate are accurate and reliable.

The chemical compound composition, calculated by Bogue equations for both Type I and Type V, are given in Table 2. It can be observed that the chemical composition of the cement from the various sources is similar with small difference between the maximum and minimum values for both types of cement. The mean values of compound composition are comparable to the typical values of Type I and Type V cements published in the literature (Komatka, 1992; Mindess, 1981; Neville, 1995) with the exception of C_3S and C_2S for Type V.

In Portland cement, C_3S and C_2S are the most important compounds, which constitute about 75% of the cement by weight and are responsible for the

Table 1. Chemical analysis of all cements

Chemical Components%	Source of Cement							
	"A"		"B"		"C"		"D"	
	Cement Type		Cement Type		Cement Type		Cement Type	
	I	V	I	V	I	V	I	V
SiO_2	19.81	20.94	21.78	22.28	20.10	20.34	20.27	21.06
Al_2O_3	6.05	3.92	4.66	3.51	5.26	4.24	6.11	4.32
Fe_2O_3	3.46	4.77	2.78	3.83	4.14	5.13	3.31	5.45
CaO	63.86	63.74	64.21	64.82	63.67	63.49	61.27	62.61
MgO	0.81	0.73	2.08	2.10	1.31	1.27	2.79	1.37
SO_3	2.16	1.88	2.17	1.86	2.11	2.14	2.12	1.92
K_2O	0.08	0.09	0.21	0.18	0.28	0.13	0.12	0.10
Na_2O	0.16	0.16	0.32	0.28	0.36	0.21	0.18	0.16
Alkali Equivalent as Na_2O	0.21	0.22	0.46	0.40	0.54	0.30	0.26	0.23
Loss on Ignition	3.35	3.56	1.46	1.24	2.76	2.62	2.56	2.74

Table 2. Chemical compound composition of all cements (calculated by Bogue equations)

Chemical Component %	Type I Cement					Type V Cement				
	Source A	Source B	Source C	Source D	Average	Source A	Source B	Source C	Source D	Average
C_3S	57.63	54.35	59.13	43.50	53.65	61.78	60.14	61.90	52.50	59.08
C_2S	13.32	21.43	13.02	25.29	18.27	13.42	18.50	11.60	20.77	16.07
C_3A	10.18	7.63	6.95	10.59	8.84	2.32	2.82	2.56	2.23	2.48
C_4AF	10.52	8.47	12.59	10.08	10.41	14.50	11.66	15.61	16.59	14.59

Table 3. Results of fineness and setting time of all cement sources

Source of Cement	Fineness of Cement m^2/kg		Setting Time (minutes)			
	Type I	Type V	Type I		Type V	
			Initial	Final	Initial	Final
A	299	310	110	155	155	200
B	333	336	155	200	205	250
C	304	287	120	160	105	150
D	282	289	115	155	155	205

strength of hydrated cement paste. As shown in Table 2, the mean values of C_3S and C_2S are 54 and 18% for Type I cement, and 59% and 16% for Type V cement. By comparison, typical values from the published literature (Komatka, 1992; Mindess, 1981; Neville, 1995) for C_3S and C_2S are 49-55% and 19-25% for Type I cement, and 38-43% and 36-43% for Type V cements, respectively. It is obvious that Type V cement produced by cement factories in the Kingdom is substantially different from typical values reported in the literature. It is interesting to observe that the C_3S and C_2S compounds of Type V cement in the Kingdom are not different from Type I cement. Therefore, the C_3A and C_4AF are the main compounds which differ between Type I and Type V cement.

Another potentially important component in cement composition is alkalis. Although Na_2O and K_2O are minor component in the cement, they are important because they have been found to react with some aggregate, known as alkali-aggregate reaction. In addition, it is reported that compressive strength has strong correlation with alkali content (in particular K_2O content) indicating that cements with a high alkali content produced concrete with lower compressive strength (Rose, 1989). It seems, however, that it is difficult to produce low alkali-cement economically in most countries. Not only the source of low alkali cements are becoming more scarce, but also modern process tend to concentrate the alkali in clinker during the manufacturing of cement (Mindess, 1981; Neville, 1995). According to ASTM C150, cement is considered low alkali cement when alkalis (equivalent = Na_2O +0.66 K_2O) is below 0.6%. The values of alkali equivalent for local cements are within the range of 0.21 to 0.54 (Table 1). By comparison, typical values from the published literature are in the range from 0.3 to 1.2% (Neville, 1995; Mehta, 1993). The results from this study clearly show that all cement produced in the Kingdom can be classified as low-alkali cement.

5.2. Cement fineness and setting time

The fineness values of both cement types from the various sources are shown in Table 3. The values are within the range of 282 to 333 m^2/kg with a mean value of 305 m^2/kg for Type I and in the range of 287 to 336 m^2/kg with a mean value of 306 m^2/kg for Type V. These values are less than the range of 350-380 m^2/kg for similar cements reported in the literature (Komatka, 1992; Mindess, 1981). However, the fineness of Saudi cement satisfy the minimum requirement of 280 m^2/kg stipulated by the ASTM C150 for both types of cement. The results of the setting time performed on the samples from the four factories are shown in Table 3. These results are within the recommended range of > 45 minutes and < 375 minutes.

5.3. Effect of cement source and type on compressive strength development

The development of strength of concrete made with both Type I and Type V from the four sources are shown in Figs. 2 and 3, respectively. These figures show that the compressive strength increases with age. Figure 2 shows that the variation in compressive strength of Type I among the four sources is limited at early age; however, the variation increases with time. For example, at 3 days, the range of variation in compressive strength of concrete made from all sources was 2.8 MPa compared to 9.2 MPa at 1 year. The same trend was also observed for Type V cement as can be seen from Fig. 3. The cause of the variation in strength among the four sources being more pronounced at later age is not clear. Some possible causes of this phenomenon could be the raw materials and the manufacturing process (Neville, 1995; Rose, 1989).

A comparison of average values of compressive strength between Type I and Type V from all cement sources for periods up to 5 years is shown in Fig. 4. It can be seen from the figure that the compressive strength for Type I cements is higher than Type V cements by about 2 to 4 MPa at all ages up to 5 years. It is established from the literature that Type V cement gain strength more slowly than Type I because of the lower C_3A content, but at later age, the strength is the same or higher. Saudi cement showed Type I to maintain at least 2 MPa advantage even at 5 years. The explanation for this unexpected behavior can be attributed to chemical composition of Saudi cement. As discussed earlier, the C_3S and C_2S contents for both Type I and Type V were similar with the major difference being the C_3A, which is higher for Type I. Therefore, the higher early strength of Type I compared to Type V was sustained with age up to 5 years.

The strength development of concrete as affected by cement source and type were examined. Table 4 shows compressive strength at all considered ages as a percentage of the 28-day strength. The results show the ratios of 3 to 28-day strength are in the range of

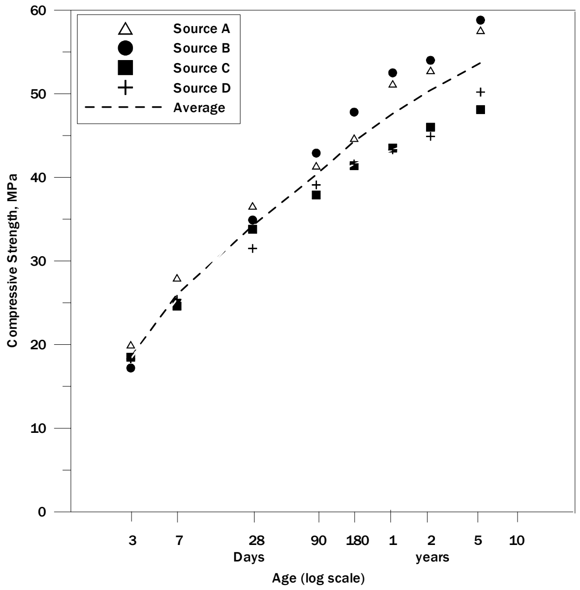

Fig. 2. Strength development of concrete made with Type I cement.

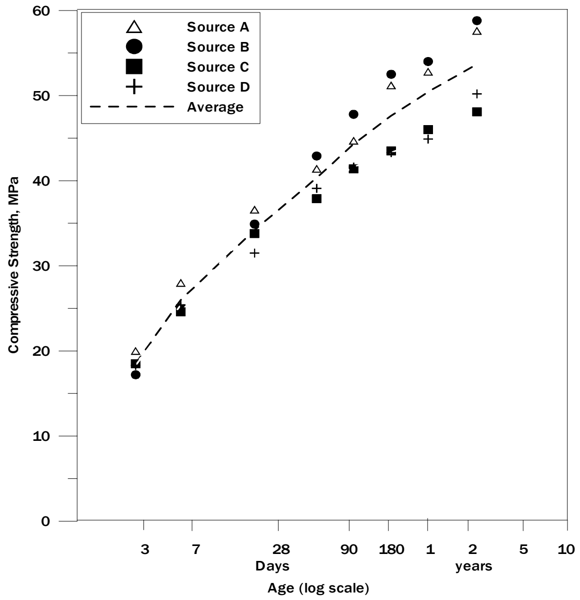

Fig. 3. Strength development of concrete made with Type V cement.

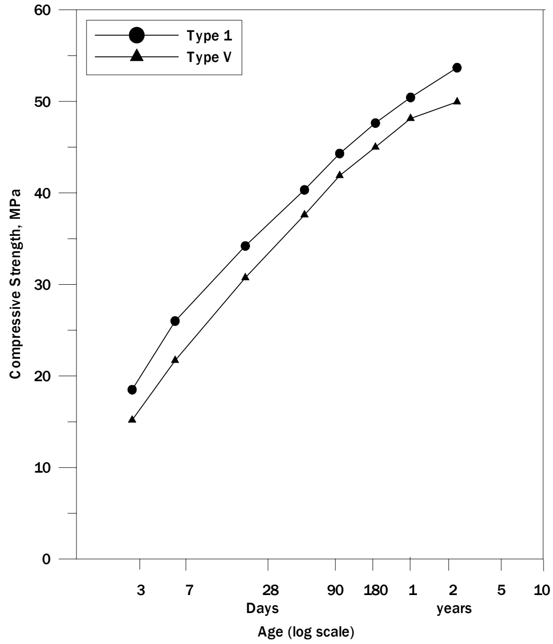

Fig. 4. Compressive strength of Type I vs. Type V.

0.49 to 0.58 with a mean value of 0.54 for Type I and 0.45 to 0.55 with a mean value of 0.49 for Type V. The ratios of 7 to 28-day strength show that the ratios fall in the range of 0.72 to 0.81 with a mean value of 0.75 for Type I and in the range of 0.68 to 0.74 with a mean value of 0.70 for Type V. These results show clearly that Type I gained strength faster than Type V at early age which is consistent with expectations based on the literature (Tuncalp, 1990). Also, the ratio of 7 to 28-day strength is similar to that reported by (Neville, 1995) for modern cement. It should be emphasized that these values are based on mixes with w/c ratio of 0.55 and plain cement without admixtures.

The strength gain beyond 28 days is affected by cement source and type. Strength gain from 28 days to 1 year was in the range of 29 to 50% with a mean value of 39% for Type I, and 35 to 60% with a mean value of 45% for Type V. The variability within each type is the effect of cement source. Also, the strength gain beyond 28 days for Type V is higher than for Type I. Based on these results, it is clear that the strength gain of Saudi cement is similar to cement in other countries (Mindess, 1981; Neville, 1995).

Table 4. Strength changes as a percentage with respect to 28-day strength

Age at Test	Type I Cement					Type I Cement				
	Source A	Source B	Source C	Source D	Average	Source A	Source B	Source C	Source D	Average
3 days	54.6	49.3	54.7	58.1	54.2	49.7	55.1	45.5	47.4	49.4
7 days	76.5	71.9	72.8	80.6	75.4	68.0	73.7	68.1	68.3	69.5
28 days	100	100	100	100	100	100	100	100	100	100
90 days	113.1	122.9	112.1	124.1	118.0	125.8	126.9	116.9	129.4	124.7
180 days	122.1	137.0	122.5	132.1	128.4	135.0	147.2	127.6	130.1	134.9
1 year	139.9	150.4	128.7	137.5	139.1	151.3	160.1	134.6	135.6	145.4
2 years	144.3	154.7	136.1	142.5	144.4	162.1	169.3	140.9	153.6	156.5
5 years	157.4	168.5	142.3	159.4	156.9	167.3	176.3	147.2	158.8	162.4

5.4. Correlation between cement properties and compressive strength

Statistical analysis between the properties of cement from all sources (chemical composition and fineness) and the compressive strength at different ages were conducted using "interactive multiple-linear regression technique". The results of multiple correlation analysis showed that the compressive strength of concrete at all ages investigated is highly dependent on the chemical composition irrespective of cement Type and source. The variables were found to correlate with compressive strength at all ages and the correlation coefficients can be used to predict the strength of concrete at different ages. For example;

28-day strength (MPa) = 11.64 + 0.85 (C_3A) + 0.23 (C_3S+C_2S).

The predicted values of compressive strength using the above equation were plotted against the experimentally obtained values as shown in Fig. 5. It can be seen that all (except one) points fall along or close to the equality line indicating the high predictive power of the equation.

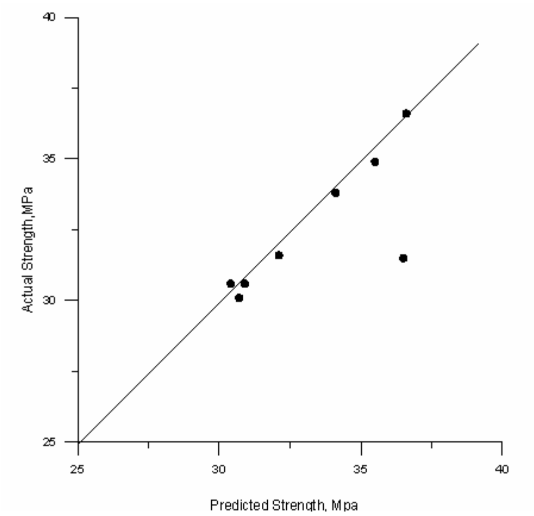

Fig. 5. Correlation between actual strengths and predicted strengths at 28 days.

6. Conclusions

1. The C_3S and C_2S compounds of Type V cement produced in the Kingdom are similar to Type I cement. The chemical compound compositions of Type I Saudi cements are comparable to the typical values of Type I cements published in the literature, but Type V showed high C_3S and low C_2S contents.
2. Based on ASTM C150 classification, cements produced in the Kingdom can be classified as low-alkali cements.
3. Compressive strength of concrete made from Type I cement gives 2-4 MPa higher strength as compared to Type V at all ages up to 5 years. The higher strength of Type I can be attributed to the fact that C_3S and C_2S contents for both Type I and Type V were similar with the major difference being the C_3A, which is higher for Type I.
4. Cement type and source plays an important role in the variation in the strength development of concrete. Type I gained strength faster than Type V at early age. The ratios of 7-day to 28-day strength are in the range of 0.72 to 0.81 with a mean value of 0.75 for cement Type I and 0.68 to 0.74 with a mean value of 0.70 for Type V.

5. Strength gain of Saudi cements is similar to cement in other countries. The strength gain from 28 days to 365 days is in the range of 29 to 50% with a mean value of 39% for Type I and 35 to 60% with a mean value of 45% for Type V.

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التركيب الكيميائي للإ نت ا نتج ا ملكة العربية السعودية
وتأث ه على قوة ا رسانة

عبد الر ن بن مد ا ز ي

قسم الهندسة المدنية ، كلية الهندسة ، جامعة الملك سعود ، ص ب ٨٠٠ ،
الرياض ١١٤٢١ ، المملكة العربية السعودية

(قدم للنشر في ٢٠٠٥/١٢/٢٠م ؛ وقبل للنشر في ٢٠٠٧/٠٤/٢٨م)

ملخص البحث. يتجاوز استهلاك الإسمنت في المملكة العربية السعودية في الوقت الحالي ٢٥ مليون طن في السنة ، ويعد معدل استهلاك الفرد في المملكة من أعلى المعدلات في العالم. يبلغ عدد شركات الإسمنت العاملة في المملكة ثمان شركات بطاقة إنتاجية تصل إلى ٢٢ مليون طن في السنة. وهناك خطط لفتح مصانع إسمنت جديدة وتوسع كبير في المصانع القائمة وهذا سيؤدي إلى زيادة الطاقة الإنتاجية الحالية إلى الضعف.

تم في هذا البحث دراسة تأثير متغيرات التركيب الكيميائي للإسمنت المُنْتَج في المملكة وتأثيره على قوة الخرسانة مع الزمن حتى عمر خمس سنوات. بيّنت نتائج الاختبارات أن التركيب الكيميائي للنوع الأول للإسمنت المُنْتَج في المملكة مشابه للنوع الأول للإسمنت الموجود في الأدبيات العالمية ، ولكن النوع الخامس كان مختلفًا في قيم C_2S و C_3S. كما وُجد أنه بالإمكان تصنيف الإسمنت المستخدم في هذه الدراسة وفقًا لـ ASTM C150 على أنه إسمنت ذو وسط قاعدي منخفض (low alkali cement). أظهرت نتائج قوة الضغط للخرسانة المُصنَّعة باستخدام النوع الأول للإسمنت أنها أعلى بحوالي ٢ إلى ٤ نيوتن/مم٢ مقارنةً بالخرسانة المُصنَّعة باستخدام النوع الخامس عند كل الأعمار حتى خمس سنوات.