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ScienceDirect
Cement & Concrete Composites 30 (2008) 290–296
Cement & Concrete Composites
www.elsevier.com/locate/cemconcomp

The influence of aggregate type on the strength and abrasion resistance of high strength concrete

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Received 13 April 2006; received in revised form 18 May 2007; accepted 25 May 2007
Available online 9 June 2007

Abstract

This paper examines the influence of aggregate type on the strength characteristics and abrasion resistance of high strength silica fume concrete. Five different aggregate types (gabbro, basalt, quartsite, limestone and sandstone) were used to produce high strength concrete containing silica fume. Silica fume replacement ratio with cement was 15% on a mass basis. Water-binder ratio was 0.35. The amount of hyperplasticizer was 4% of the binder content by mass. Gabbro concrete showed the highest compressive and flexural tensile strength and abrasion resistance, while sandstone showed the lowest compressive and flexural tensile strength and abrasion resistance. High abrasion resistant aggregate produced a concrete with high abrasion resistance.

Three-month compressive strengths of concretes made with basalt, limestone and sandstone were found to be equivalent to the uniaxial compressive strengths of their aggregate rocks. However, the concretes made with quartsite and gabbro aggregate showed lower compressive strength than the uniaxial compressive strength of their aggregate rocks.

Keywords: Aggregate types; Concrete; Strength; Abrasion

1. Introduction

Compressive strength of concrete has been accepted as the most important mechanical property of structural concrete. The relationship between concrete composition and compressive strength has long been a matter of interest for researchers [1]. The factors influencing the strength of concrete are: the amount and type of cement, w/c ratio, aggregate type and grading, workability of fresh concrete, mineral admixtures used, chemical additives, curing conditions and time, etc.

de Larrard and Belloc [1] have reported that the strength of a concrete is determined by the characteristics of the mortar, coarse aggregate, and the interface. For the same quality mortar, different types of coarse aggregate with different shapes, textures, mineralogy, and strengths may result in different concrete strengths. However, one of the concepts is the limitation of the water/cement ratio (W/C) to produce high strength and high performance concrete in which the aggregate plays a more important role.

According to Wu et al. [2], high strength concrete is usually made with a W/C less than 0.4, and the strength of the mortar and the bond at the interface may be similar to the strength of the coarse aggregate. In such a case, it may be possible to make use of the full potential of the coarse aggregate particles.

Effects of coarse aggregate type on mechanical properties of concretes with different strengths were reported by Özturan and Çeçen [3]. They have concluded that normal strength concretes made with basalt and gravel gave similar

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doi:10.1016/j.cemconcomp.2007.05.011

compressive strength while limestone concrete attained a somewhat higher strength. Higher tensile strengths were obtained with crushed basalt and limestone compared to the gravel aggregate when used in high strength concrete.

Zhou et al. [4] studied the effect of coarse aggregate on the compressive strength of high performance concrete. They reported that weaker aggregates reduced the strength of concrete. Similarly, Aitcin and Mehta [5] reported that, for identical materials and similar mix proportions, using diabase and limestone aggregates produced concrete with significantly higher strength than those using granite and river aggregate.

Bishr et al. [6] reported the results of a study conducted to investigate the influence of coarse aggregate quality on the compressive strength and split tensile strength of high strength concrete. Based on the experimental study, they concluded that the quality of coarse aggregate significantly influenced the compressive strength and split tensile strength of high strength concrete. Steel slag aggregate had the highest compressive and split tensile strength while calcerous limestone had the lowest.

The effect of four coarse aggregate types on the compressive strength and flexural strength of normal and high strength concrete were reported by Ezeldin and Aitcin [7]. It was reported that the type of the coarse aggregate did not greatly influence the mechanical properties of normal strength concrete. However, the high strength concrete mixtures containing the limestone aggregate produced higher compressive strength than the concrete mixtures containing gravel or granite aggregate. It was also reported that the flexural behaviour of high strength concrete was not influenced by the aggregate types.

Many of these researchers did not represent the aggregate strength in comparison with the concrete strength. The sand used in their study was different type from the coarse aggregate used in concrete. Ezeldin and Aitcin [7] reported that aggregate type did not influence the flexural tensile strength; contrary to this Bishr et al. [6] reported that aggregate type influenced split tensile strength. Additionally, they did not consider the influence of aggregate types on abrasion resistance of concrete.

This paper presents the results of a laboratory investigation carried out to study the influence of five different types of aggregate on the compressive strength, flexural tensile strength and abrasion resistance of high strength concrete. The results of the current investigation show how aggregate strength limits the compressive and flexural tensile strengths of a concrete, how transition zone strength limits the compressive strength of concrete, and how aggregate types influence abrasion resistance of concrete.

2. Materials and experimental procedure

2.1. Cement

The cement used was ASTM Type I normal Portland cement with a specific gravity of 3.15 g/cm^3. Nominal strength of cement, obtained with a standard mortar test using RILEM procedure, was 53.9 MPa at 28 days with standard moist curing. Initial setting time of the cement was 2 h, and final setting time was 5 h. The Blaine specific surface area was 3350 cm^2/g and the chemical oxide compositions are given in Table 1.

2.2. Silica fume

Silica fume (SF) was supplied from Antalya-Etibank Ferro-Crome Factory (Turkey). Its chemical oxide composition is given in Table 1. The specific gravity and unit weight were 2.32 and 245 kg/m^3, respectively. The remaining of the silica fume on 45 μm sieve was 4.8%.

2.3. Aggregate types and grading

Five types of crushed aggregates gabbro, basalt, quartsite, limestone and sandstone were used as the aggregates in the production of concrete to investigate the effect of the aggregate rocks on the compressive strength, flexural strength and abrasion resistance of concrete. Gabbro was an intrusive igneous rock which consists of plagioclase, olivine and clinopyroxene. Its texture is typically granular and hypidiomorphic. Basalt was an extrusive igneous rock which consists of plagioclase and pyroxene. It showed a texture from holocrystaline to hypocrystaline; grain size, generally fine with rare plagioclase and pyroxene. Quartsite was a regional metamorphic rock which consists of quartz mineral and as the accessories mineral; mica. Limestone was an organogenetic sedimentary calcareous rock. It was fine grain sized and had a compact texture. Sandstone was a sedimentary rock, which consists of fine grain sized quartz mineral and altered feldspar.

The uniaxial compressive strengths (UCS) of aggregate rocks were determined using cylindrical specimens cored with 42 mm diameter and 85 mm length. The ends of the specimens were made flat and perpendicular to the axis of the specimen. Their sides were smoothed and polished, and specimens were inspected to be free of cracks, fissures, veins, and the other flaws which would act as selective planes of weakness and cause an undesirable change of the real properties of the rocks.

Compressive strength, standard Los Angeles abrasion index, shore hardness, specific gravity, water absorption ratio and porosity index of the aggregate rocks were presented in Table 3.

Aggregates were crushed and separated according to their size. It was sieved using standard sieves and separated into seven groups consisting of 0–0.25, 0.25–0.50, 0.50–1, 1–2, 2–4, 4–8 and 8–16 mm. The combinations of separated aggregates were obtained with such a grading that complies with the requirements of TSI 706 [8]. Grading of mixed aggregates was presented in Table 2. Mixed aggregate grading was between the lower limit and medium limit of the standard which was required. Aggregates were used in dry conditions for the production of the concretes.

Table 1
Chemical composition of cement and silica fume (%)

Oxide	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	K_2O	Na_2O	LOI
Cement	20.62	5.65	4.05	62.08	2.55	2.57	0.81	0.12	1.55
Silica fume	85.93	0.64	0.32	0.70	4.91	0.63	NA	NA	2.66

Table 2
Grading of crushed aggregates with standard limit for all aggregate type

Sieve (mm)	% Passed			
	TS 706 lower limit	TS 706 medium limit	TS 706 upper limit	Mixed aggregate
16	100	100	100	100
8	60	76	88	64
4	36	56	74	41
2	21	42	62	27
1	12	32	49	17
0.50	7	20	35	11
0.25	3	8	18	5

2.4. Mixture composition and sample preparation

The proportion of the concretes mixtures were 1:4:0.35 cement, mixed aggregate and water-binder ratio, respectively by mass. The approximate quantity of binder content (NPC + SF) was 475 kg/m^3, which corresponds to the category of high performance concrete. Amount of silica fume content was 15% of the total binder content (71 kg/m^3).

A commercial carboxic type hyperplasticizer was employed to maintain a constant workability of slump in the order of 10–15 cm (see Table 4). Amount of hyper plasticizer was 4 % of the binder content by mass. Table 4 shows that the slump workabilities of concrete produced with different aggregate were within the target workability. Only the sandstone concrete showed very low slump workability, due to the feldspar mineral in the sandstone was highly altered and changed to clay. The mixing water was absorbed by the altered feldspar and decreased the slump of fresh concrete.

Cubic samples with a 100 mm side, and prismatic samples with the dimensions of $100 \times 100 \times 500$ mm were cast from the fresh concrete mixtures. The compaction of the samples was obtained by means of vibration. There was no difficulty observed while compacting and preparing sandstone concrete specimens.

All the test specimens were demoulded at 1 day, and then cured in water. Curing temperature was 22 ± 2 °C.

Table 4
Slump workability of concrete made with different aggregate type (cm)

Concrete	Gabbro	Basalt	Quartsite	Limestone	Sandstone
Slump	10	15	10	12	2

For each age, three specimens were employed in compression and flexural tensile strength measurement for each type of concrete. The compressive strength and the flexural tensile strength of concretes were measured at 3, 7, 28 days, and 3 months. The strength measurements were carried out using ELE 3000 kN hydraulic press.

Two types of specimens were prepared for abrasion measurement. Cubic samples with a 71 mm side were prepared for surface abrasion test by means of Dorry type Bohme apparatus described in TSI 699 [9]. In compliance with TS 699, the abrasion system had a steel disc, which had a diameter of 750 mm and rotating speed of 30 ± 1 cycle/min, a counter and a lever, which could apply 300 ± 3 N on the specimens. In the test procedure, 20 ± 0.5 g of abrasion dust was spread on the disc, the specimens were then placed, the load was applied to the specimen and the disc was rotated for four periods, while a period was equal to 22 cycles. After that, the surfaces of the disc and the sample were cleaned. The above-mentioned procedure repeated for 20 periods (totally 440 cycles) by rotating the sample 90° in each period. The volume decrease was measured in cm^3/50 cm^2 due to wear. Abrasive dust used in this test was corundum (crystalline Al_2O_3). The abrasion test was carried out at 28 days. Prismatic specimens with the dimensions of $50 \times 50 \times 100$ mm were prepared for Los Angeles abrasion measurement. Cubic samples and prismatic specimens prepared for abrasion measurement were obtained by means of saw cutting. Three specimens were used for each abrasion tests method. The concrete samples to be abraded were placed into Los Angeles abrasion machine without steel ball, and the average weight loss, as abrasion, was determined in percent at 100 and 500 revolutions.

Table 3
Aggregate type, strength, shore-hardness and Los Angeles abrasion

Aggregate rock type	UCS (MPa)	Abrasion (%) (L.A 500)	Shore-hardness	Specific gravity (g/cm^3)	Water absorption (%)	Porosity (%)
Gabbro	247	11.06	79	2.846	0.14	0.40
Basalt	132	23.66	67	2.739	2.29	4.21
Quartsite	160	16.20	60	2.781	0.18	0.44
Limestone	110	24.14	47	2.674	0.42	1.13
Sandstone	52	96.18	34	2.664	2.63	5.63

3. Results and discussion

3.1. Compressive strength of concrete versus compressive strength of aggregate

The average compressive strength of concretes made with gabbro, basalt, quartsite, limestone and sandstone aggregates at 3, 7, 28 and 90 days are illustrated in Table 5, separately. For a better comparison purpose, the compressive strengths of aggregates were also presented in Table 5.

Table 5 shows that, the compressive strengths of the gabbro concrete were 63.8 MPa, 79.9 MPa, 119.4 MPa, and 136.4 MPa at 3, 7, 28, and 90 days curing time. The basalt concrete developed the compressive strengths of 76.2 MPa, 90.5 MPa, 121.2 MPa and 134.6 MPa at 3, 7, 28 and 90 days curing time. Compressive strengths of the quartzite concrete reached 58.1 MPa, 63.5 MPa, 97.4 MPa and 103 MPa at 3, 7, 28 and 90 days curing time. The limestone concrete developed 57.4 MPa, 64.2 MPa, 96.3 MPa and 107.7 MPa at 3, 7, 28 and 90 days curing time, respectively. The compressive strengths of sandstone concrete were 43.4 MPa, 44.4 MPa, 50.3 MPa, 53.0 MPa at 3, 7, 28 and 90 days.

The inclinations of the increases of the compressive strengths of concretes excluding sandstone concrete are concordant with the normal concrete. This is expected due to hydration of binder.

Based on the experimental results presented in Table 5, it can be concluded that the compressive strength of concrete increases as the compressive strength of the aggregate rock increases.

Considering the compressive strength results of concrete at 3 months, Table 5 shows that the concrete made with sandstone developed a 53 MPa compressive strength, while the compressive strength of sandstone was 52 MPa. Compressive strength of limestone concrete was 107.7 MPa at 3 months, while the compressive strength of limestone was 110 MPa. Quartsite concrete reached a compressive strength of 103 MPa at 3 months, while the compressive strength of its rock was 160 MPa. Compressive strength of basalt aggregate was 132 MPa, and the compressive strength of basalt concrete was 134.6 MPa at 3 months. Concrete made with gabbro developed a 136.4 MPa compressive strength, while the strength of gabbro was 247 MPa.

Table 5
Compressive strength of concretes at different times

Curing time (days)	Compressive strength (MPa)				
	Gabbro (247)	Basalt (132)	Quartsite (160)	Limestone (110)	Sandstone (52)
3	63.8	76.2	58.1	57.4	43.4
7	79.9	90.5	63.5	64.2	44.4
28	119.4	121.2	97.4	96.3	50.3
90	136.4	134.6	103.0	107.7	53.0

Although the compressive strength of paste was not measured separately, it could be assumed that the compressive strength of paste is about 136.4 MPa. The assumption is made on the basis of the compressive strength result obtained from concrete made with gabbro and compressive strength of gabbro aggregate rock. Gabbro aggregate rock had a rough surface and higher strength than strength of gabbro concrete. The assumption made is supported by the visual examination of the broken specimen subjected to compression test. Visual examination of failure plane of tested specimen showed that the cracks passed through the mortar and paste, and failure of the aggregate was not observed. Therefore, it was found that the paste strength limited the compressive strength of the concrete (136.4 MPa) made with gabbro, while compressive strength of gabbro was 247 MPa. It was concluded that the paste strength limited the compressive strength of concrete made with gabbro aggregate. In this case, full potential of the strength of coarse aggregate was not utilized. A paste with higher strength has to be used to make use of the full potential strength of gabbro aggregate.

For the basalt aggregate case, it was concluded that the uniaxial compressive strength of basalt aggregate (132 MPa) and paste strength (assumed to be 136.4 MPa) limited the compressive strength of concrete (134.6 MPa). It was observed from the tested specimen that the cracks passed through the aggregate and paste. Both full potential strength of paste and aggregate was utilized since the compressive strength of basalt and paste were equivalent.

It was observed that the compressive strength of limestone aggregate (110 MPa) limited the compressive strength of limestone concrete (107.7). Obviously, the uniaxial compressive strength (52 MPa) of sandstone limited the compressive strength of concrete (53 MPa), since the compressive strength of paste was about 136 MPa. This phenomenon can be explained as the ceiling effect reported by de Larrard and Belloc [1]. Visual examination of failure plane of tested specimen (for limestone and sandstone concrete) showed that the crack passed through the aggregate, and most of the aggregate was cracked and broken. When a comparison was made between the compressive strength of concrete and the uniaxial compressive strength of corresponding aggregate, it can be concluded that the full potential of the paste strength could not make use when sandstone and limestone were incorporated in concrete. In this case, the strength of aggregate limited the concrete strength (ceiling effect).

Moreover, neither compressive strength of quartsite rock nor the compressive strength of paste limited the compressive strength of concrete made with quartsite aggregate, but it was the texture of quartsite that limited the compressive strength of quartsite concrete since the texture of quartsite aggregate was smooth which provided lower adherence and bond strength. This event was also supported by the visual examination of broken concrete specimens. Examination of failure plane of specimen showed that the most of the cracks developed at the weak interface around the coarse aggregate resulting coarse aggregate taken out from their socket. In this case, neither the full potential of paste nor aggregate strength was utilized, since the texture of quartsite that had smooth surface lowered the strength of bond and adherence of the paste in the interfaces.

3.2. Flexural strength of concrete versus compressive strength of aggregate

The average flexural tensile strength of concretes made with gabbro, basalt, quartsite, limestone and sandstone aggregates at 3, 7, 28 and 90 days are illustrated in Table 6, separately. For a better comparison purpose, the compressive strengths of aggregate were also presented in Table 6 with flexural tensile strength of concrete produced.

Table 6 shows that, similar to compressive strength, flexural tensile strength increases with the increase of curing time for each concrete. Considering flexural tensile strength results of concrete at 3 months, Table 6 shows that the concrete made with sandstone developed a 5.6 MPa flexural tensile strength. Limestone concrete developed a 13.9 MPa flexural tensile strength. Quartsite concrete developed a 16.9 MPa flexural tensile strength. Basalt concrete developed a 17.6 MPa flexural tensile strength. Concrete made with gabbro developed a 18.4 MPa flexural tensile strength. Sandstone concrete showed the lowest flexural tensile strength, while gabbro concrete showed the highest flexural tensile strength.

The obtained tensile strength presented in Table 6 seemed to be high. This was found to be parallel to the finding of Ezeldin and Aitcin [7] who reported that it was possible to obtain a relatively high flexural tensile strength/compressive strength ratio at high compressive strength.

The concrete sequence in terms of flexural tensile strength from the lowest to highest was sandstone, limestone, quartsite, basalt and gabbro. However, the concrete sequence in terms of compressive strength of the aggregate rocks from the lowest to highest was sandstone, limestone, basalt, quartsite and gabbro. In flexural tensile strength case basalt and quartsite swapped. This can be explained by the smooth surface of quartsite aggregate that provided weak bond and adherence between aggregate and mortar interface.

Table 6
Flexural strengths of concretes at different curing times

Curing time (days)	Flexural tensile strength (MPa)				
	Gabbro (247)	Basalt (132)	Quartsite (160)	Limestone (110)	Sandstone (52)
3	12.6	11.4	12.9	7.9	3.2
7	16.1	15.4	14.9	12.5	4.5
28	17.3	16.7	16.2	12.8	5.2
90	18.4	17.9	16.9	13.9	5.6

3.3. Relationship of compressive and flexural tensile strengths of concrete to compressive strength of aggregate

A regression analysis was carried out to establish a relationship of compressive strength and flexural tensile strength of concrete to aggregate rock strength. Analyses of the results were presented in Figs. 1 and 2 which show that an acceptable relationship exists between aggregate compressive strength and concrete compressive and flexural tensile strength, the correlation coefficient was in the order of 80%. Accordingly, it can be concluded that as the aggregate strength increases, the compressive strength and flexural tensile strength of concrete increase.

3.4. Relation between compressive strength of aggregate and abrasion of aggregate

Compressive strength of aggregate rocks and Los Angeles abrasion values of aggregates were presented in Table 3.

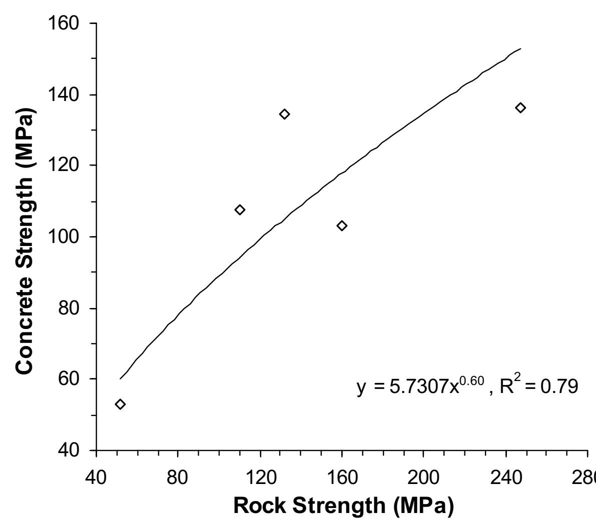

Fig. 1. The relationship between compressive strength of concrete and compressive strength of aggregate rock.

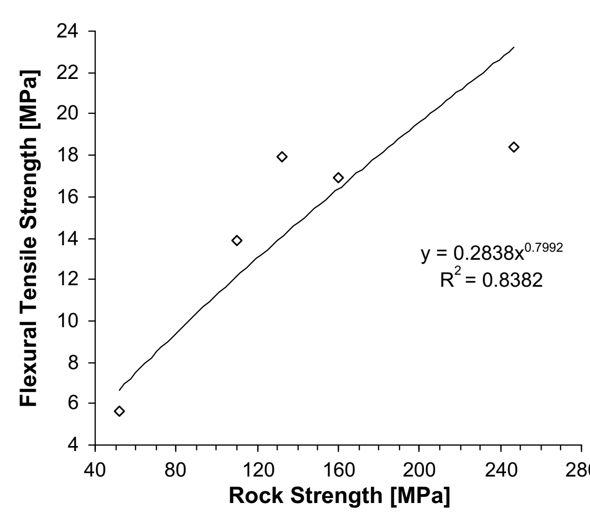

Fig. 2. The relationship between flexural tensile strength of concrete and compressive strength of aggregate rock.

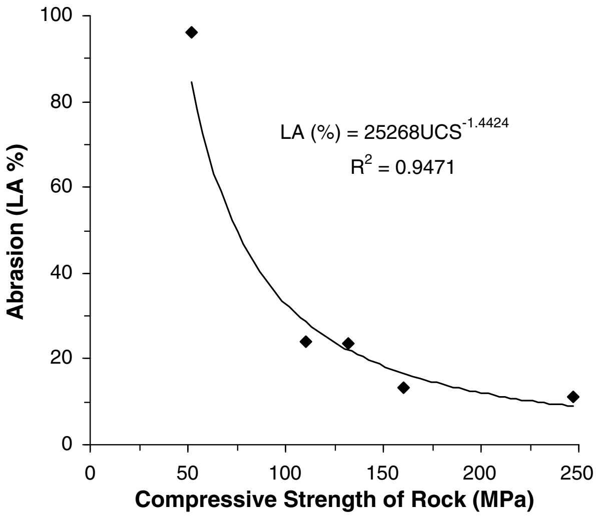

Fig. 3. The relationship between Los Angeles abrasion index and compressive strength of aggregate rocks.

A regression analysis was carried out between compressive strength and abrasion value of aggregate; it was presented in Fig. 3. Fig. 3 shows that a strong exponential relationship with 0.95 R^2 existed between the compressive strength of aggregate rocks and Los Angeles Abrasion Index. It should be noted that, this relationship is established for aggregate rock strength between 50–250 MPa. In addition, Table 3 and Fig. 3 also show that abrasion resistance of aggregate increases as the compressive strength of rock increases.

3.5. Relationship of strength and hardness of aggregate to abrasion of concrete produced

Abrasion values of concrete obtained from Los Angeles abrasion machine and Bohme apparatus were presented in Table 7 together with the compressive strength of aggregate and concrete, and shore-hardness index of aggregate. It can be seen from Table 7 that, in general, there is a relation existed between compressive strength of concrete and abrasion of concrete, strength of aggregate and abrasion of concrete, shore hardness of aggregate and abrasion of concrete. Abrasion of concrete decreases as the strength of aggregate, the strength of concrete, and shore-hardness index increases.

Table 7
Abrasion indexes of concretes

Rock	UCS of rock	UCS of concrete	Shore index	Bohme	LA-100	LA-500
Gabbro	247	136.4	79	6.5	4.3	11.8
Basalt	132	134.6	67	7.3	5.2	15.5
Quartsite	160	103.0	60	6.9	5.6	14.3
Limestone	110	107.7	47	8.1	7.7	24.6
Sandstone	52	53.0	34	9.7	8.9	28.5

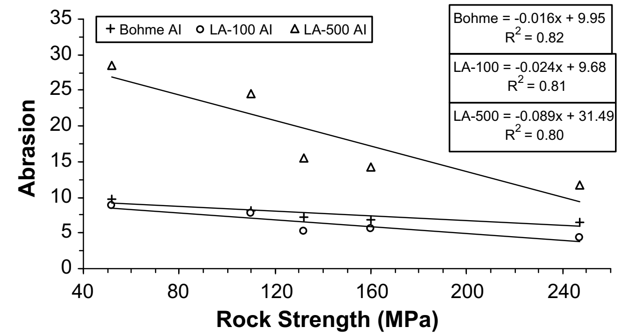

Fig. 4. Relationship between abrasion of concrete and rock strength.

A linear regression analysis was carried out to establish a relationship between rock strength and concrete abrasion value obtained from Los Angeles machine and Bohme apparatus. The results obtained were presented in Fig. 4. Fig. 4 shows that an acceptable linear relationship exists between concrete abrasion and aggregate strength, it was found that the correlation coefficients of R^2 were in the order of 80%.

The results of the linear regression analyses, which are carried out between Los Angeles abrasion of concrete and shore-hardness index of aggregate, and between Bohme abrasion of concrete and shore-hardness index of aggregate were presented in Figs. 5 and 6. Figs. 5 and 6

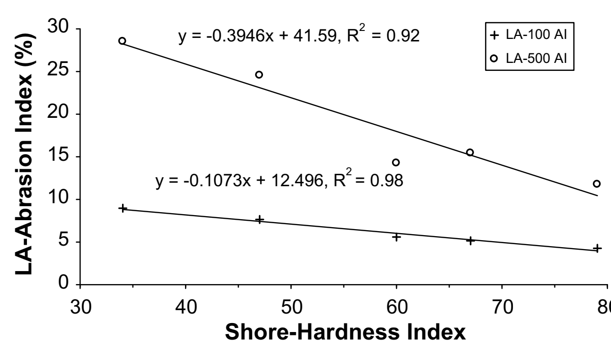

Fig. 5. Relation between shore-hardness index and Los Angeles abrasion of concrete.

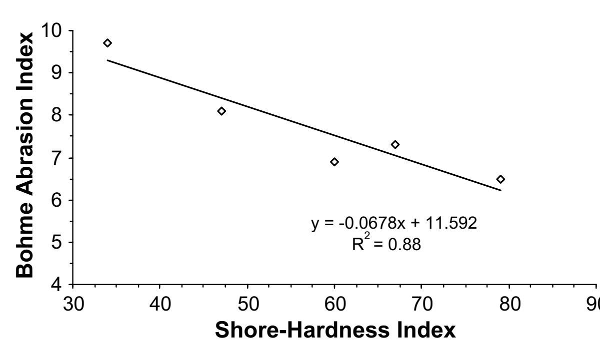

Fig. 6. Relation between shore-hardness index and bohme abrasion of concrete.

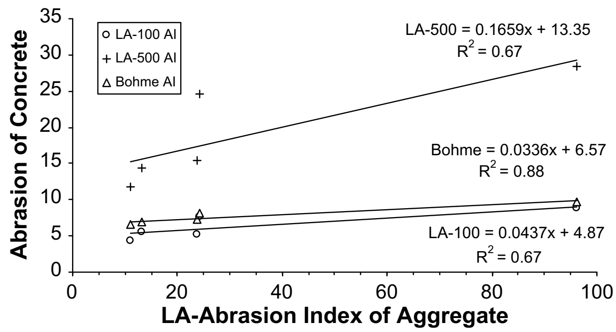

Fig. 7. Relation between abrasion of aggregate and abrasion of concrete.

show that a strong relationship exists between abrasion and shore-hardness index. Correlation coefficient of R^2 was found to be in the order of 90% and higher. These relationships were found to be stronger than that of the relationship established between abrasion of concrete and compressive strength of aggregate.

3.6. Relation between abrasion of aggregate and abrasion of concrete

The relationships between Los Angeles abrasion of aggregate and Los Angeles abrasion of concrete were established at 100 and 500 revolutions. Additionally, a relationship was established between Los Angeles abrasion of aggregate and Bohme abrasion index of concrete. The results obtained were presented in Fig. 7. Correlation coefficient of R^2 for the relationship between Los Angeles abrasion of aggregate and Los Angeles abrasion of concrete was 67% for both 100 and 500 revolutions. It was, however, 88% for the relationship between Los Angeles abrasion of aggregate and Bohme abrasion index of concrete produced.

4. Summary and conclusions

In this study, influence of aggregate type on the compressive strength, flexural tensile strength and abrasion resistance of concrete were investigated using constant mixture proportions. Five different aggregate types (gabbro, basalt, quartsite, limestone and sandstone) were used in the concrete mixtures. The results of the investigation showed that aggregate strength and texture influenced the compressive strength, flexural tensile strength and abrasion resistance of concrete. Compressive strength of basalt, limestone and sandstone limited the compressive strength of the concrete produced with corresponding aggregate. Texture of quartsite limited the compressive and flexural strength of concrete. Paste and mortar strength limited the compressive strength of concrete made with gabbro.

A good relationship was established between aggregate compressive strength and LA-abrasion of aggregate. A relationship was existed between aggregate compressive strength and strength of concrete for both compressive strength and flexural tensile strength, correlation coefficients of R^2 were in the order of 80%. A good relationship was existed between rock strength and LA-abrasion of concrete, rock strength and Bohme abrasion of concrete, correlation coefficients of R^2 were in the order of 80%. A strong relationship existed between shore-hardness index of aggregate and LA-abrasion of concrete with R^2 of 90% or higher. Correlation coefficient (R^2) of the relationship between shore-hardness of aggregate and Bohme abrasion of concrete was in the order of 90%. Interestingly, the relationship established between abrasion of concrete and LA-abrasion of aggregate showed that a stronger relationship existed between LA-abrasion of aggregate and Bohme abrasion of concrete than that of LA-abrasion of aggregate and LA-abrasion of concrete.

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