MECHANICAL PROPERTIES OF HIGH-STRENGTH CONCRETE INCORPORATING DIFFERENT COARSE AGGREGATE

Adel Kurdi
Structural Engineering Department, Faculty of Engineering,
Alexandria University, Alexandria, Egypt.

SYNOPSIS

An experimental study investigated the effect of coarse aggregate characteristics on the compressive strength, splitting tensile strength, flexural strength, and elastic behavior of high-strength concrete and mortar. Nine mixes of high-strength concrete containing limestone, granite, and gravel coarse aggregates were used and a total of 360 concrete specimens were tested. It was found that limestone-aggregate concrete produced significantly higher strength than those using granite and gravel. Mortar was extracted by sieving part of each concrete through a No. 4 sieve. The concrete strength is limited by the strength of mortar. Under compressive loads, concretes achieved lower strengths than mortars by about 94, 83, and 70 percent for limestone- aggregate concrete, granite-aggregate concrete, and gravel-aggregate concrete, respectively. The gravel-aggregate concrete has smaller splitting tensile strength and flexural strength than the crushed rock aggregate concrete (limestone-aggregate concrete and granite aggregate concrete) by about 7 and 9 percent respectively, regardless the water cement ratio of the concrete mixes and the ages of concrete specimens. The matrix-aggregate bond is lower for gravel, but it is higher with limestone and granite). For the types of coarse aggregates used in the present investigation, the highest modulus of elasticity of concrete was achieved in limestone-aggregate concrete followed by granite-aggregate concrete and gravel-aggregate concrete. The different characteristics of the aggregate types are responsible for this behavior of high-strength concretes, and the superior performance of limestone-aggregate concrete compared to the granite-aggregate concrete and gravel-aggregate concrete is self-evident.

INTRODUCTION

The development of high-strength concrete has been gradual over many years. As the development has continued, its definition has changed. In the 1950s, concrete with a compressive strength of 34 MPa was considered high strength. In the 1960s, concrete with 41 and 52 MPa compressive strength were used commercially. In the early 1970s, 62 MPa concrete was being produced. More recently, compressive strength over 110 MPa have been considered for applications in cast-in-place buildings and prestressed concrete members. Many studies [1,2] have shown that for optimum compressive strength with high cement content and low water to cement ratios, the maximum size of coarse aggregate should be kept to a minimum. The bond to a 76 mm aggregate particle was only about 0.1 of that to a 13 mm particle. Smaller aggregate sizes are also considered to produce higher concrete strengths because of less severe concentrations of stress around the particles, which are caused by differences between the elastic modulii of the paste and the aggregate [2].

Many studies have shown that crushed stone produces higher strengths than rounded gravel. The most likely reason for this is the greater mechanical bond which can develop with angular particles. Because, as stated earlier, bond strength is the limiting factor in the development of high-strength concrete, the mineralogy of the aggregates should be such as to promote chemical bonding. Some work has been done with artificial materials such as Portland and aluminous cement clinkers and selected slags [3], but the long-term stability of the clinkers is in question.

In conventional concrete < 41 MPa, the strength-limiting is not significantly affected by the properties of coarse aggregate because the weakest components in concrete are the hardened cement paste and the transition zone between cement paste and coarse aggregate rather than the coarse aggregate itself. When designing conventional concrete mixtures, the mineralogy of coarse aggregate is not a matter of concern unless the aggregate contains some constituents that could have a deleterious effect on the durability of concrete. For high-strength > 41 MPa, researchers have observed that the hardened cement paste and the transition zone are no longer strength-limiting. The mineralogy and strength of the coarse aggregate itself control the ultimate strength of concrete.

The 91-day compressive strengths using three different coarse aggregates in superplasticised concrete mixtures with identical materials and properties (W/C = .24) were 93, 103, and 83 MPa respectively, for calcareous-limestone, dolomitic-limestone, and quartzitic-gravel aggregates [4]. High-strength concrete exhibits less internal microcraking than lower-strength concrete for a given imposed axial strain [5]. The relative increase in the lateral strains is less for high-strength concrete. The lower relative lateral expansion during the inelastic range may mean that the effect of triaxial stresses will be proportionally different for high-strength concrete. It was reported that the effectiveness of spiral reinforcement is less for high-strength concrete [6].

The shape of the ascending part of the stress-strain curve is more linear and steeper for high-strength concrete, and the strain at the maximum stress is slightly higher for high-strength concrete [7]. The values for the modulus of elasticity of high-strength concretes have been reported in the range of 31 to 45 GPa depending mostly on the method of determining the modulus [8]. Dewar [9] studied the relationship between the indirect tensile strength and the compressive strength of concretes having compressive strengths of up to 83.79 MPa at 28 days. He concluded that at low strengths, the indirect tensile strength may be as high as 10 percent of the compressive strength but at high strengths it may reduce to 5 percent. He observed that the tensile splitting strength was about 8 percent higher for crushed rock aggregate concrete than for gravel aggregate concrete, he also found that the indirect tensile strength was about 70 percent of the flexural strength at 28 days.

RESEARCH SIGNIFICANCE

It is apparent from the work of previous authors t the mineralogical characteristics of coarse aggreg has a significant effect on the mechanical properties high-strength concrete. This paper contributes to t discussion of the influence of coarse aggreg characteristics on the compressive, splitting tensi flexural strength, and modulus of elasticity, of hi strength concrete mixtures made with the types coarse aggregate being considered.

EXPERIMENTAL INVESTIGATION PROCEDUR

Three series of test specimens were casted usi Ordinary Portland cement. The coarse aggregates use in series I, II, and III were limestone, granite, an gravel respectively with maximum size of 19 mm One aggregate consisted of round and smooth partic of a siliceous gravel and the other two consisted crushed particles with rough surface. Particles of a aggregates appeared to be clean, hard, strong, an mineralogically uniform. The fine aggregate used fo making all the concrete mixtures were a natural silic sand with 2.4 fineness modulus. Assuming both fin and coarse aggregates to be in saturated surface dr (S.S.D) condition. Adjustments in batch weights wer made to correct for the true water content of sand limestone, granite, and gravel. A high rang superplasticiser with specific weight of 1.17 t/m^3 an based on modified ligno-sulfonates and polyoxycarbo acids was used for all mixes. The water to cement rati was .275, .30, and .35 by weight. There was a total o nine high-strength concrete mixes comprising thre types of coarse aggregate with three values of water t cement ratio. Table (1) summarizes the composition o concrete mixes. Mortar was obtained by sieving part o each concrete through a No. 4 sieve. Various tests o hardened concrete and mortar were carried out Compressive and splitting tensile strength wer determined on 100x200 mm. cylindrical specimens Static modulus of elasticity was measured on 150x30 mm. cylindrical specimens. Flexural strength o 150x150x750 mm. prisms were determined. Al concrete specimens were covered with wet burlap fo 24 hr, then removed from the molds and cured unde water until testing. All concrete specimens were teste at the ages of 7, 28, and 90 days from casting. Th results reported at any particular age are the average o three specimens.

Table 1. Concrete mix proportions.

Series	Mix	Mix proportions, kg/m^3				W/C	Super. l/m^3
		Cement	Sand	Coarse	Water		
I Lime	L1	550	670	974	192.5	.35	5.5
	L2	550	670	1034	165	.30	11.55
	L3	550	670	1066	151.5	.275	13.75
II Granite	GN1	550	670	996	192.5	.35	5.5
	GN2	550	670	1058	165	.30	11.55
	GN3	550	670	1090	151.5	.275	13.75
III Gravel	GR1	550	670	959	192.5	.35	5.5
	GR2	550	670	1019	165	.30	11.55
	GR3	550	670	1050	151.5	.275	13.75

Table 2. Properties of mortar after 28 days.

W/C	Compressive-MPa	Tensile-MPa	Flexural-MPa	Modulus-GPa
.35	73.2	5.4	8.4	32.5
.30	90	6.7	11	37.5
.275	98.7	7.3	11.5	40.8

Table 3. Compressive strength and modulus of elasticity of high-strength concrete containing different aggregate types.

Series	Mix	Compressive strength-MPa			Modulus of elasticity-GPa		
		7 days	28 days	90 days	7 days	28 days	90 days
I	L1	50.7	68.8	73.5	32.6	34.5	35.5
	L2	61.3	84.6	90.5	35.4	38.9	40.5
	L3	67.2	92.8	101.5	36.3	42.9	43.5
II	GN1	47.1	59.8	66.1	28.8	30.7	32
	GN2	57.9	73.8	79.7	32.2	34.9	36.1
	GN3	64.4	81.2	89.9	33.8	38.8	39.6
III	GR1	33.6	51.2	57.9	25.8	28.9	30.2
	GR2	41.8	63.1	65.4	28.8	32.1	33.6
	GR3	44.8	69.1	78.8	29.6	35.1	37

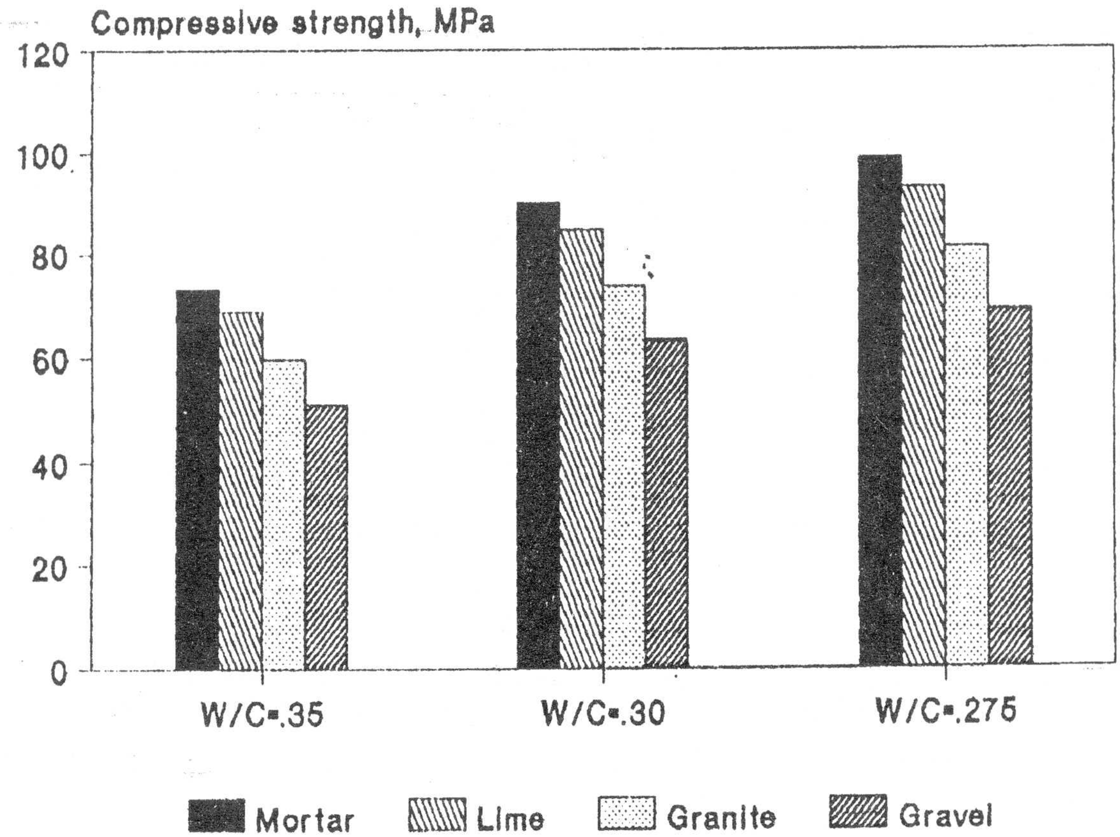

Figure 1. Compressive strength of mortar and high-strength concrete containing different aggregate types at days.

Table 4. Splitting tensile and flexural strengths of high-strength concrete containing different aggregate types

Series	Mix	Splitting tensile strength-MPa			Flexural strength-MPa		
		7 days	28 days	90 days	7 days	28 days	90 days
I	L1	4.5	5	5.7	6.9	7.4	7.8
	L2	5.4	6.2	6.7	7.5	9.3	9.5
	L3	5.6	6.7	7.9	7.9	10.3	10.7
II	GN1	4.1	4.8	5.4	6.1	6.9	7.3
	GN2	5	5.9	6.3	7.2	8.9	9.2
	GN3	5.6	6.5	7.1	7.8	9.7	10.1
II	GR1	3.5	4.2	4.8	4.9	5.9	6.1
	GR2	4.1	4.8	5.3	6.1	7.3	7.5
	GR3	4.6	5.2	5.9	6.3	8	8.5

TEST RESULTS AND DISCUSSION

All the mortars were extracted by sieving part of each concrete through a No. 4 sieve. For the same water to cement ratio the mortars extracted from limestone aggregate concrete, granite-aggregate concrete, and gravel-aggregate concrete were tested and, as they presented no differences in their properties, the mean values were reported in Table (2). For concretes with water to cement ratio of .30 and after 28 days, the average value of mortar compressive strength extracted from limestone-aggregate concrete, granite-aggregate concrete, and gravel-aggregate concrete was 90 MPa. This value is considered a strength limit for the high-strength concrete mixtures.

The tests results showed that all concrete mixes had slightly more than 100-mm. slump, and the fresh concrete density varied from 2340 to 2440 kg/m^3.

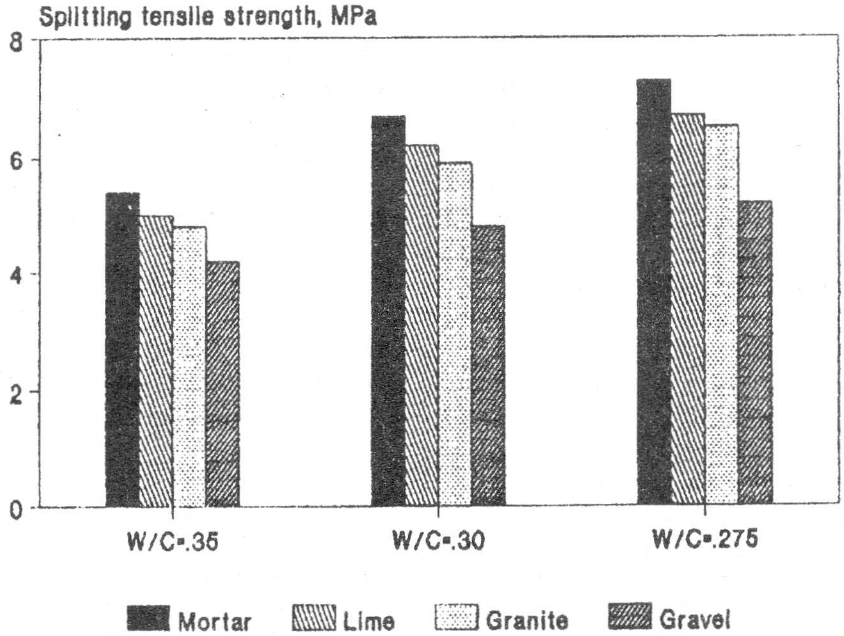

Figure 2. Splitting tensile strength of mortar and high-strength concrete containing different aggregate types at 28 days.

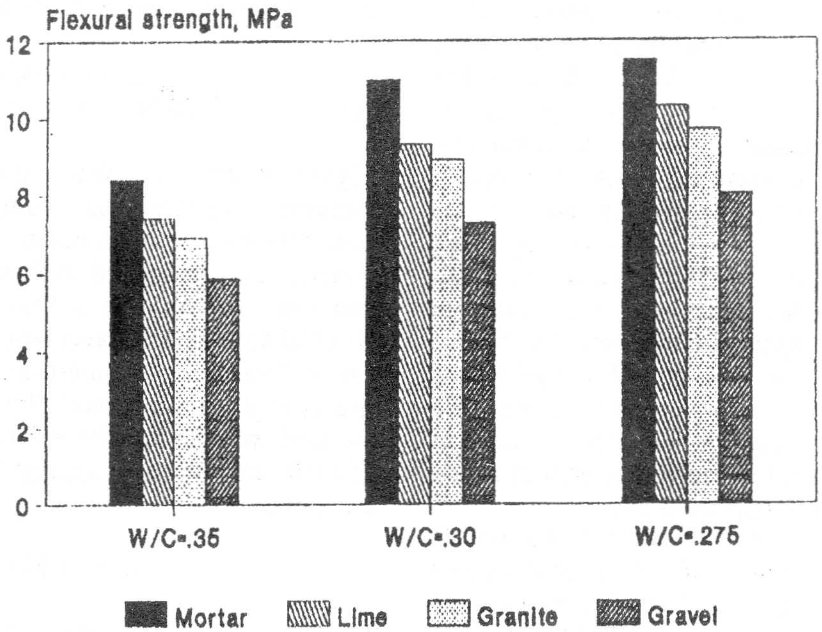

Figure 3. Flexural strength of mortar and high-strength concrete containing different aggregate types at 28 days.

Table (3) shows the compressive strength and modulus of elasticity of high-strength concretes with limestone, granite, and gravel aggregates respectively.

Figure (1) shows the 28-day compressive strength of various high-strength concrete mixes compared to that of mortar. At 7, 28 and 90 days, the average compressive strengths of limestone-aggregate concrete, granite-aggregate concrete, and gravel-aggregate concrete were 94, 83, and 70 percent of the mortar strength respectively regardless of the water cement ratio of the concrete mixes and the ages of concrete specimens. For gravel-aggregate concrete with water to cement ratio of .30, the 28-day compressive strength were reduced significantly to 63.1 MPa and the strength was approximately 25 percent lower when compared with the limestone-aggregate concrete.

Although gravel-aggregate concrete can also be considered as high-strength (f_c > 41 MPa), there are important differences in its behavior. Most of the fracture surfaces pass through the transition zone between cement paste and coarse aggregate. This may be attributed to the weak transition zone in the gravel-aggregate concrete as proved from the cases of aggregate-cement paste debonding. In granite-aggregate concrete with water to cement ratio of .30, the 28-day compressive strength was 73.8 MPa and most cracks pass though coarse aggregate particles. There was no evidence of any failure in the transition zone. For limestone-aggregate concrete, with water to cement ratio of .30, a 28-day compressive strength of 84.6 MPa was obtained and the examination of the failed specimens showed no evidence of aggregate cement paste debonding, but the occurrence of fractured aggregates is strongly reduced. This is indicated that the limestone aggregate used in this investigation was indeed a strong aggregate. However a significant difference was noted between the types of fractured aggregates in the limestone-aggregate and in the granite-aggregate concrete. In the limestone-aggregate concrete, the fracture surfaces represented the same plane passing though the paste and the aggregate particle. In the granite-aggregate concrete, the failure occurred earlier within weaker particles than in the transition zone or the hardened cement paste. The differences in the crack pattern and, consequently in strength must be attributed to the characteristics of the different types of coarse aggregates used.

Figure (2) and Figure (3) show the splitting tensile strength and flexural strength of mortar and various high-strength concrete after 28 days. Unlike compressive strength, as shown in Table (4), the flexural strength and splitting tensile strengt limestone-aggregate concrete were closer to the gra aggregate concrete.

Figure (4) shows the observed relationship betw the splitting tensile and compressive strengths limestone-aggregate concrete, granite-aggreg concrete, and gravel-aggregate concrete. As can seen from the figure, the splitting tensile strengt gravel-aggregate concrete is less than those limestone-aggregate concrete and granite aggreg concrete for the same compressive strength.

For limestone-aggregate concrete, the relations between the splitting tensile strength f_{sp} MPa and compressive strength f_c MPa follows the equation:

$$f_{sp} = 0.681(f_c)^{.5}$$

for 50.7 MPa $< f_c <$ 101.5 MPa

For granite-aggregate concrete, the relations between the splitting tensile strength f_{sp} MPa and compressive strength f_c MPa follows the equation:

$$f_{sp} = 0.677(f_c)^{.5}$$

for 47.1 MPa $< f_c <$ 89.9 MPa

From equations 1, and 2 the properties of regression curves for limestone-aggregate concrete granite-aggregate concrete were so close that a sin regression curve could be used for the combinatio all the data points of the two concretes.

For gravel-aggregate concrete, the relations between the splitting tensile strength f_{sp} MPa and compressive strength f_c MPa follows the equation:

$$f_{sp} = 0.633(f_c)^{.5}$$

for 33.6 MPa $< f_c <$ 78.8 MPa

Figure (5) shows the observed relationship between flexural strength and compressive strength limestone-aggregate concrete, and granite-aggrega concrete also compared to that of the gravel-aggrega concrete. As for the splitting tensile strength, flexural strength of gravel-aggregate concrete was a lower than those of limestone-aggregate concrete a gravel aggregate concrete. The relationship between flexural strength f_r MPa and the compressive streng f_c MPa for limestone-aggregate concrete, follows equation:

$$f_r = 0.981(f_c)^{.5}$$

for 50.7 MPa $< f_c <$ 101.5 MPa

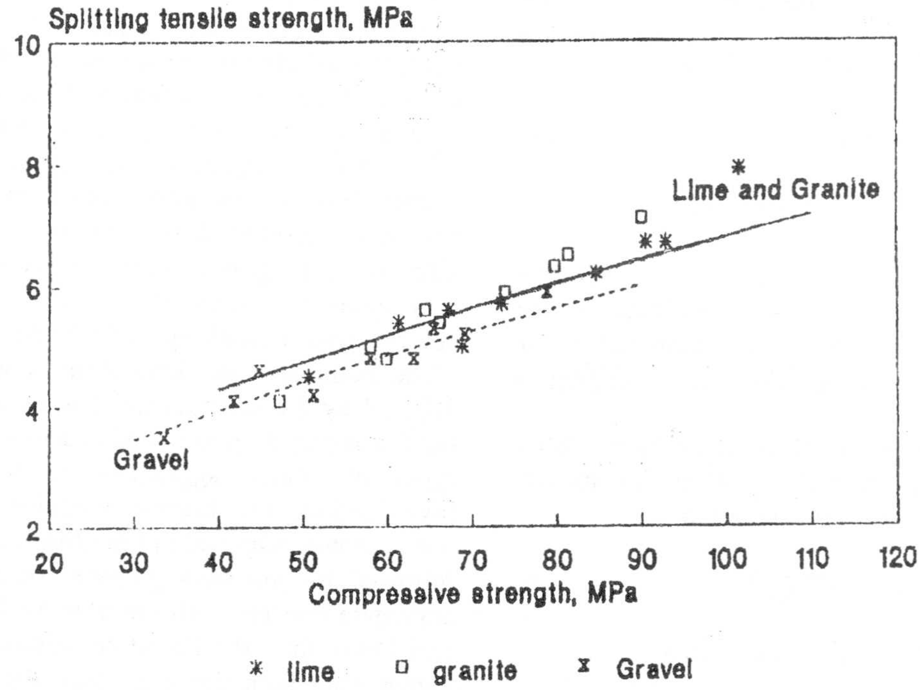

Figure 4. Relationship between splitting tensile strength and compressive strength of high-strength concrete containing different aggregate types.

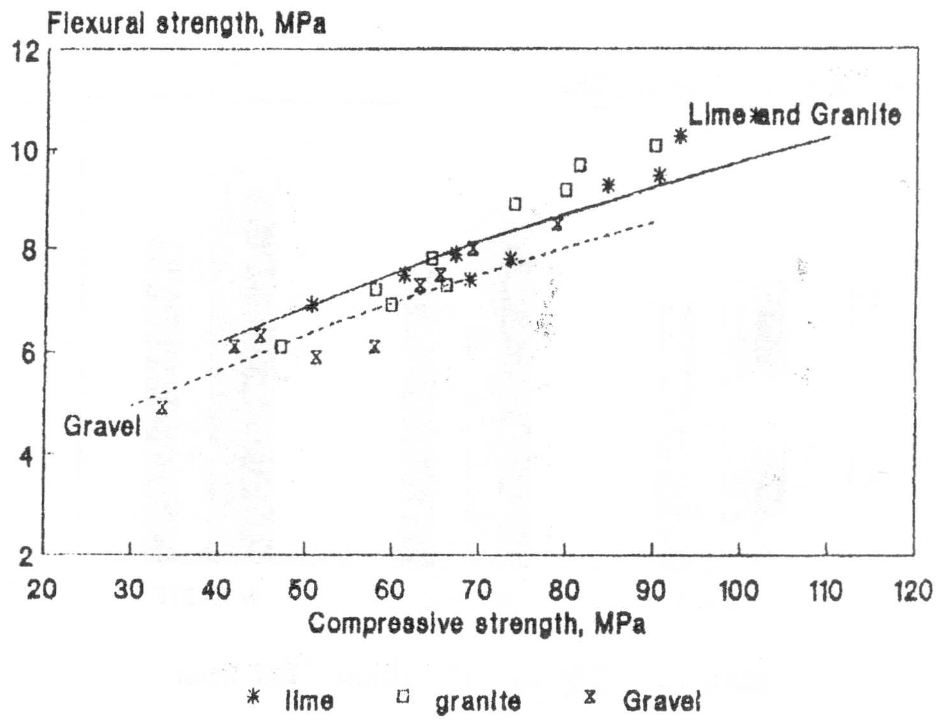

Figure 5. Relationship between flexural strength and compressive strength of high-strength concrete containing different aggregate types.

The relationship between the flexural strength f_r MPa and the compressive strength f_c MPa for granite-aggregate concrete, follows the equation:

$$f_r = 0.978(f_c)^{.5} \qquad (5)$$

for $\qquad 47.1 \text{ MPa} < f_c < 89.9 \text{ MPa}$

As for splitting tensile strength, a single regration curve could be used for the relationship between the flexural strength f_r and the compressive strength f_c for limestone-aggregate concrete and granite-aggregate concrete.

The relationship between the flexural strength f_r MPa and the compressive strength f_c MPa for gravel-aggregate concrete, follows the equation:

$$f_r = 0.902(f_c)^{.5} \qquad (6)$$

for $\qquad 33.6 \text{ MPa} < f_c < 78.8 \text{ MPa}$

The gravel-aggregate concrete has smaller splitting tensile strength and flexural strength than the crushed rock aggregate concrete (limestone-aggregate conc and granite aggregate concrete) by about 7 an percent respectively, regardless of the water cem ratio of the concrete mixes and the ages of conc specimens. The matrix-aggregate bond is lower gravel, but it is higher with limestone and granite. T results show a good agreement with those of Dev [9], who reported 8 percent lower splitting tens strength for gravel-aggregate concrete than corresponding crushed rock concrete havi compressive strength up to 83.79 MPa at 28 days.

The modulus of elasticity of the concrete is primar affected by the stiffness and volume of the aggrega but the aggregate-paste bond is also important. For t types of coarse aggregates used in the prese investigation, the highest modulus of elasticity concrete was achieved in limestone-aggregate concre followed by granite-aggregate concrete and grav aggregate concrete. The mortar modulus of elastici was lower than the limestone aggregate concrete b higher than both the granite-aggregate concrete a gravel-aggregate concrete as shown in Figure (6).

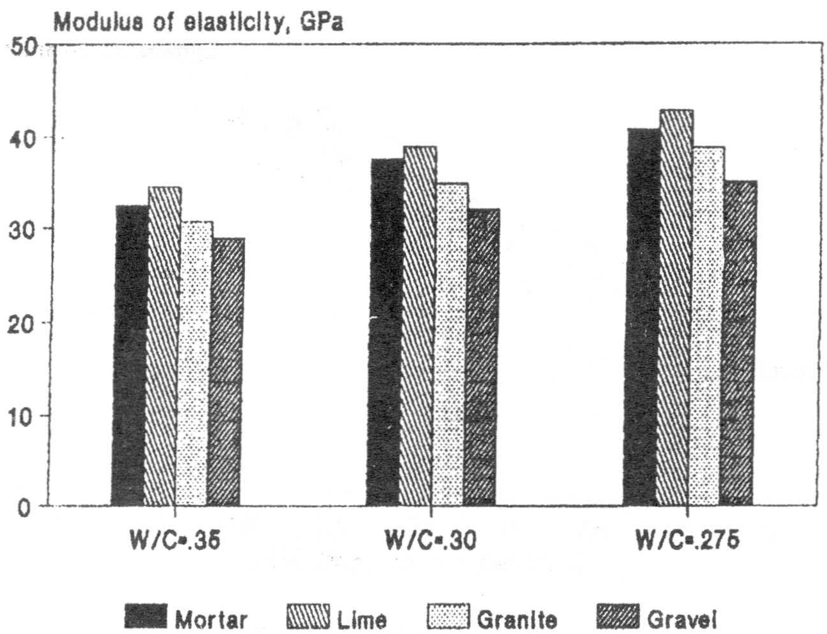

Figure 6. Modulus of elasticity of mortar and high-strength concrete containing different aggregate types at 28 days.

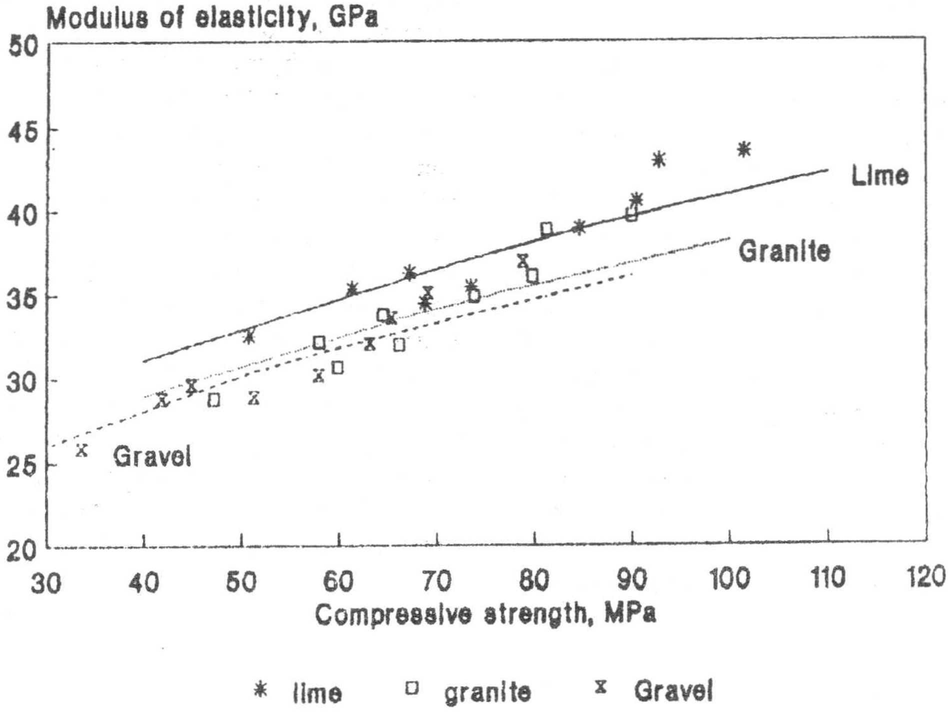

Figure 7. Relationship between modulus of elasticity and compressive strength of high-strength concrete containing different aggregate types.

Figure (7) shows the relationship between static modulus of elasticity and compressive strength for limestone-aggregate concrete, granite-aggregate concrete, and gravel-aggregate concrete. The modulus of elasticity of the concrete is primarily affected by the stiffness and volume of the aggregate, but the aggregate-paste bond is also important.

For limestone-aggregate concrete, the observed relationship between modulus of elasticity strength E_c GPa and the compressive strength f_c MPa follows the equation:

$$E_c = 10.304(f_c)^{.3} \qquad (7)$$

for $50.7 \text{ MPa} < f_c < 101.5 \text{ MPa}$

For granite-aggregate concrete, the observed relationship between modulus of elasticity strength E_c GPa and the compressive strength f_c MPa follows the equation:

$$E_c = 9.593(f_c)^{.3} \qquad (8)$$

for $47.1 \text{ MPa} < f_c < 89.9 \text{ MPa}$

For gravel-aggregate concrete, the observed relationship between modulus of elasticity strength E_c GPa and the compressive strength f_c MPa follows the equation:

$$E_c = 9.371(f_c)^{.3} \qquad (9)$$

for $33.6 \text{ MPa} < f_c < 78.8 \text{ MPa}$

As can be seen from equations 7, 8, and 9, the static modulus of elasticity of gravel-aggregate concrete is less than those of granite-aggregate concrete and limestone-aggregate concrete for the same compressive strength.

Qualitatively, it seems that the concrete generally becomes more brittle when the strength increases. There is much less information available, however, as to the quantitative aspect of the stress-strain behavior of high-strength concrete. This is mainly due to the difficulty of measuring the complete stress-strain curve, particularly for the descending part of the stress-strain curve. Nevertheless, it seems that the ascending branch of the stress-strain curve becomes more linear as the strength of the concrete increases. While the descending branch of the curve becomes much sleeper. As shown in Figure (8), for limestone-aggregate concrete, the shape of the ascending part of the stress-strain curve is more linear than for the granite-aggregate concrete or gravel-aggregate concrete. The unstable descending parts of the curves were not measurable with the experimental setup used. The highest modulus of elasticity of concrete was achieved in limestone-aggregate concrete, followed by granite-aggregate concrete and gravel-aggregate concrete. The unrecoverable plastic strain in the hysteresis loop during the unloading applied through measuring the 28-day modulus of elasticity (40 percent of the ultimate strength, ASTM C 469) were 20, 40, and 90 microstrain for limestone-aggregate concrete, granite-aggregate concrete, and gravel-aggregate conc respectively. The values of the unrecoverable pla strain in the hysteresis loop were probably related the strength of the transition zone between cem paste and coarse aggregate. The presence of la values of unrecoverable plastic strain proba indicated the weakness of the transition zone, wh led to microfracturing even at low levels of appl stresses within the elastic range [10]. The limesto aggregate concrete gave the smallest unrecovera plastic strain. A possible chemical interaction betw the calcite in the limestone and calcium hydroxide the hydrated cement paste can be held accountable the high strength of the transition zone in t limestone-aggregate concrete [11]. Thus, the stre strain diagram depends very much on the properties the coarse aggregate used.

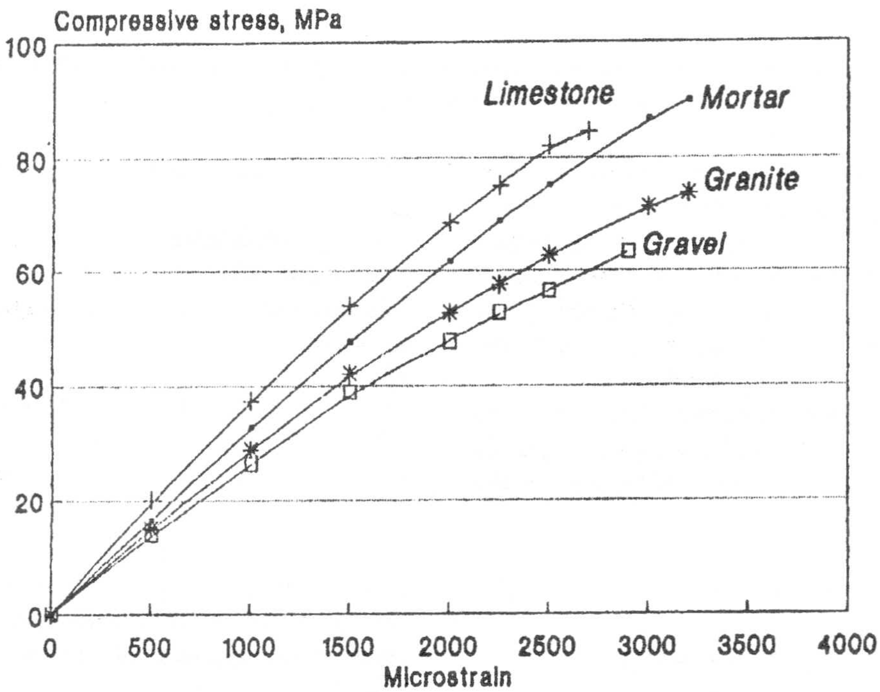

Figure 8. Stress-strain curves of mortar and high-strength concrete containing different aggregate types at 28 days with water to cement ratio of 0.30.

CONCLUSIONS

The following conclusions have been derived from the study findings:

1- The characteristics of coarse aggregate is the primary factor controlling the strength of high-strength concrete. By using three different types of coarse aggregate in high-strength concrete, compressive strength, splitting tensile strength, flexural strength, and modulus of elasticity were shown to be significantly influenced by the characteristics of the coarse aggregate. The limestone-aggregate concrete gave the best results, followed by granite-aggregate concrete and gravel-aggregate concrete. In high-strength, because matrix strength is close to aggregate strength, the probability of crack development through aggregates increases, and the mechanisms of cracking are modified compared with conventional concrete.

2- Concrete strength of high-strength concrete is limited by the strength of its mortar. Under compressive loads concretes achieved lower strengths than mortars by 94, 83, and 70 percent for limestone-aggregate concrete, granite-aggregate concrete, and gravel-aggregate concrete respectively regardless of the water cement ratio of the concrete mixes and the ages of concrete specimens.

3- Very useful information about the aggregate characteristics can be provided by the examination of the stress-strain curves and the fractured specimens after the compression test. For limestone-aggregate concrete, the shape of the ascending part of the stress-strain curve becomes more linear than that of granite-aggregate concrete or gravel-aggregate concrete.

4- In the case of limestone-aggregate concrete, a small value of unrecoverable plastic strain within the elastic range, was indicative of a strong aggregate and a strong transition zone between the aggregate and cement paste in concrete. In the case of granite-aggregate concrete, and gravel-aggregate concrete, a high unrecoverable plastic strain was indicative of an inherent weakness in the aggregate particles, or a weak transition zone.

5- The gravel-aggregate concrete has smaller splitting tensile strength and flexural strength than the crushed rock aggregate concrete (limestone-aggregate concrete and granite aggregate concrete) by about 7 and 9 percent respectively, regardless of the water cement ratio of the concrete mixes and the ages of concrete specimens.

REFERENCES

[1] R.L. Blick, "Some factors influencing high-strength concrete", *Modern concrete,* V. 36, No. 12, Apr. 1973, pp. 38-41.

[2] W.A. Cordon and H.A. Gillespie, "Variables in concrete aggregates and Portland cement paste which influence the strength of concrete", *ACI Journal,* Proceedings V. 60, No. 8, Aug. 1963, pp. 1029-1052.

[3] "Tentative interim report of high strength concrete", *ACI Journal,* Proceedings V. 64, No. 9, Sept. 1967, pp. 556-557.

[4] P.C. Aitcin, S.L. Sarkar and D. Yaya, "Microstructural study of different types of very high-strength concrete", *Proceeding, MRS Symposium,* V. 85, Materials research society, Pittsburgh, 1987, pp. 261-272.

[5] R.L. Carrasquillo, F.O. Slate and A. Nilson, "Microcracking and behavior of high-strength concrete subject to short-term loading," *ACI Journal,* proceedings V. 78, No. 3, May-June 1981, pp. 179-186.

[6] S.H. Ahmad and S.P. Shah, "Stress-strain curves of concrete confined by spiral reinforcement," *ACI Journal,* proceedings V. 79, No. 6, Nov.-Dec. 1982, pp. 484-490.

[7] S.P. Shah, "High strength concrete, a workshop summary," *Concrete international: Design and construction,* V. 3, No. 5, May 1981, pp. 94-98.

[8] S.H. Ahmad, "Properties of confined concrete subjected to static and dynamic loading," *PhD thesis, University of Illinois at chicago circle,* Mar. 1981.

[9] J.D. Dewar, "The indirect tensile strength of concretes of high compressive strength," Technical report No. 42.377, *Cement and concrete association, Wexham springs,* Mar. 1964, 12 pp.

[10] P.C. Aitcin and P.K. Mehta, "Effect of coarse-aggregate characteristics on mechanical properties of high-strength concrete," *ACI Journal,* proceedings V. 87, No. 2, March-April 1990, pp. 103-107.

[11] P.J. Monteiro, and P.K. Mehta, "Interaction between carbonate rock and cement paste," *Cement and concrete research,* V. 16, No. 2, Mar. 1986, pp. 127-134.