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High Strength Natural Lightweight Aggregate Concrete with Silica Fume

by A. Yeğinobalı, K.G. Sobolev, S.V. Soboleva and M. Tokyay

Synopsis: High strength lightweight aggregate concretes are usually produced using special artificial aggregates together with mineral and chemical admixtures. Using natural lightweight aggregates instead of processed artificial aggregates can significantly reduce cost of such concretes.

Turkey has rich reserves of volcanic tuff and pumice stones. In Turkish standards highest strength classes for lightweight tuff and pumice concretes are 30 and 16 MPa, respectively. In this research selected samples of these lightweight rocks were used to produce high strength lightweight aggregate concretes. The binding medium was made of portland cement, silica fume and superplasticizing admixture. For each concrete mixture properties such as workability, unit weight, compressive strength at various ages, as well as splitting tensile strength, modulus of elasticity and thermal conductivity values were determined to find the optimum quantities of materials to be used.

Tests show that it is possible to produce a natural lightweight aggregate concrete with a 28-day compressive strength of 55 MPa, a dry unit weight in the range of 1700-2100 kg/m^3 and coefficient of thermal conductivity value of about 0.55 W/m^{2}K.

Mathematical equations based on experimental results were obtained by regression analyses. The equations are useful for optimizing concrete mixtures for specified unit weight and compressive strength.

Keywords: concrete; high- strength; lightweight aggregate; mix proportioning; modulus of elasticity; pumice; silica fume; splitting tensile strength; superplasticizer; thermal conductivity; unit weight.

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INTRODUCTION

Recent developments in high-strength concrete are based on the use of very effective combinations of high range water reducers and silica fume [1]. One of the application areas for high-strength cement based materials is lightweight concrete. The lightweight concrete with increased strength or decreased unit weight can be produced based on system of portland cement - silica fume - superplasticizer. These investigations have demonstrated the possibilities of producing high strength lightweight aggregate concrete using selected artificial lightweight aggregates [2-4].

Turkey has rich reserves of volcanic tuffs and pumice that can be used as natural lightweight aggregates (NLWA). Usually such lightweight rocks are used for non-structural concrete due to their low strength level.

In Turkish standards the highest strength classes for lightweight tuffs and pumice concretes are limited to 30 and 16 MPa, respectively. Using silica fume and a superplasticizer for improving binder strength and natural lightweight aggregates (NLWA) instead of processed artificial aggregates, the cost of structural concretes can be reduced.

There were no sufficient data available concerning mixture proportioning and behaviour of this new type of concrete that can be useful for structure design and application. In 1993, Scientific and Technical Research Council of Turkey (TÜBİTAK) started a new research program devoted to utilisation of NLWA for production of structural high strength concretes. The main objective of this program was to make some experimental data available, as well as to provide industry with an indication of the performance for this new class of concrete.

A research study in which selected samples of NLWA were used to produce strengths up to 55 MPa NLWA concrete was carried out. The silica fume and superplasticizer were used to provide high strength level of NLWA based concrete. For each concrete mixture properties such as workability, bleeding, plastic shrinkage, unit weight, compressive strength at 7, 28, 90 days as well as splitting tensile strength, modulus of elasticity and thermal conductivity values were determined.

Mathematical equations based on processing of experimental were obtained by regression analyses. The equations are useful for optimising concrete mixtures for designed unit weight and compressive strength.

The investigation results presented in this paper is part of a more extensive research program including tests of more than 70 different concrete and mortar mixtures.

EXPERIMENTAL PROGRAM

Materials

The coarse natural lightweight aggregates were crushed tuff (T1) and four types of crushed pumice rocks (P1, P2, P3, P4) with optimal grading in accordance with TS 706 "Aggregates for Concrete". Maximum aggregate size was 19 mm. The 1- hour specific gravity factor was 2.15 for tuff and 1.06-1.39 for different types of pumice (as per method presented in reference [5]). The 1- hour absorption was 19 % for tuff and 16-21% for different types of pumice. The properties of the NLWA used are presented in Table 1. Local natural sand with fineness modulus 3.18 was used as fine aggregate.

Normal portland cement PC 42.5 meeting requirements of the relevant Turkish Standard TS 19 "Cement - Portland Cement" was used in concrete mixtures T1, P1, P3 and P4 type of NLWA. Blended cement PC 32.5 containing 15% of trass as natural pozzolan made in accordance with TS 10156 "Cement - Blended Cement" was used in concrete mixtures for P2 type of NLWA.

A locally available ferrosilicon condensed silica fume was used. The physical properties and chemical composition of cements and silica fume are given in Table 2. Commercially available melamine based high range water reducing agent (Melment-L10/33) was used.

Mixing Procedure

All materials were batched by weight. The following mixing procedure was used for concrete production. The coarse lightweight aggregates were placed in the bowl and total amount of the 1- hour absorbing water was added to saturate aggregates. After 15 minutes the NLWA, cement, silica fume and sand were placed in the mixer and mixed for 1 minute. The remaining water and superplasticizer were added and mixing continued for a further 3 minutes.

Test Procedure

The workability (slump and VB value), air content and fresh unit weight were determined according to TS 2871/TS3115 "Measuring the Consistency of Concrete", TS 2901 "Determination of Air Content of Fresh Concrete by the Pressure Method" and TS 2941 "Determination of Unit Weight, Yield and Air Content of Fresh Concrete".

All the specimens were cast using a external vibrator, and were initially cured under plastic cover sheets for 24 hours, after which they were demoulded, capped and cured in curing room at 95% relative humidity and 20 ^{0}C. The 150x150x150 mm cube and 150x300 mm cylinder specimens were used for determination of the concrete properties.

The compressive strength, splitting tensile strength, modulus of elasticity and Poisson's ratio tests were performed according to TS 3114 "Determination of Compressive Strength of Concrete Test Specimens", TS 3129 "Splitting Tensile Strength of Cylindrical Concrete Specimens" and TS 3114 "Test Method for Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression".

A test procedure similar to the one presented in reference [6], was used for evaluating the effects of aggregate type, mixture proportions and workability level on plastic shrinkage and water loss of concrete. The screeding speed of airflow was 10 m/min and temperature of airflow was 20 ^{0}C and 30 ^{0}C.

Concrete Mixture Proportions

The specific gravity factor method was used in order to calculate mixture proportions of structural NLWA concrete with desirable unit weight, compressive strength and workability [5]. Special attention was paid to the natural lightweight aggregate properties and optimal gradation of the aggregates.

The NLWA concrete mixtures with high cement content 405 - 610 kg/m^3 at the low W/C of 0.21-0.39 and fine to NLWA ratios of 0.35 - 1.70 were investigated. The silica fume at the 5 - 27% content in total cementing materials was used. High range water reducing admixture (Melment - L10/33) has been used at the dosage of 0.5 - 3.5% of total cementing materials to produce a low W/C. All of the concrete mixtures were adjusted to provide slump level between 4 - 8 cm. The mixture proportions of typical NLWA concretes are presented in Table 3. Mixture designations adopted for the Table 3 and in this paper are based on the type of NLWA used.

TEST RESULTS AND DISCUSSION

PROPERTIES OF FRESH CONCRETE

Workability

In all concrete mixtures with W/C of 0.21 - 0.39 and different SF contents the optimal superplasticizer dosage was adjusted from 0.5 to 3.5 % of total cementitious materials to provide the slump in the range of 4 - 8 cm. VB value was measured to make a comparison of workability level between different concrete mixtures. The relationship between slump and VB value is presented in Fig. 1.

Fresh Unit Weight

The fresh unit weight of the NLWA concrete mixtures ranged from 1870 to 2280 kg/m^3 (Fig. 3). Fig. 2 shows the unit weight loss of the NLWA concretes with drying.

The relationship between the dry unit weight and fresh unit weight of NLWA concretes is presented in Fig. 3.

This chart demonstrates the trend to decrease the difference between the dry and fresh unit weight for more dense concretes.

Air Content

Air contents of fresh concretes varied from 1.0 to 5.0% and average amount of entraining air was 2 %.

Bleeding and Setting Time

No bleeding of the NLWA concretes with silica fume and superplasticizer was found. Reference NLWA concretes without silica fume and superplasticizer have very low bleeding due to bonding of free water by porous aggregates.

The NLWA concrete mixture posses some reduction of the setting time, which leads to loss of workability after 1 hour. Use of saturated NLWA and large dosage of superplasticizer compensates for this problem.

Plastic Shrinkage

The formation of plastic shrinkage cracks on the NLWA concrete surface was detected at air temperature of 30^0C. The total crack area and crack length was reduced by increasing NLWA and silica fume contents. No plastic shrinkage of the NLWA concrete was found at 20^0C. It was found that the amount of evaporated water is reduced as the amount of water absorbed by NLWA increases.

MECHANICAL PROPERTIES OF CONCRETE

Compressive Strength

The compressive strength results of NLWA concretes are summarised in Table 3. For the different mixtures the 28- day compressive strength varied from 17.5 to 53.0 MPa.

The most important factor affecting the strength of NLWA concrete is the free W/C and Fig. 4 gives that relationship.

Use of silica fume and superplasticizer at optimal amounts results for a low free W/C of around 0.21 - 0.25. The optimal amount of silica fume was adjusted between 10 and 15 % as it shown in Fig. 5. From the previous study, the optimal superplasticizer dosage was found to be close to 10% of silica fume weight [7].

The total cementitious materials content has significant influence on the compressive strength of the NLWA concretes. Fig. 6 demonstrates that increasing the total cement content from 445 kg/m^3 to 633 kg/m^3

allows a rise in the compressive strength from 29.3 to 53.0 MPa. No difference was found in 28- day behaviour of NLWA concretes based on blended cement containing 15% of trass as natural pozzolan.

Fig. 7 shows the relationship between the dry unit weight and 28- day compressive strength of NLWA concretes. This graph demonstrates the trend of increasing strength with increasing density for the particular mixtures used.

These relationships between the 28- day compressive strength, dry unit weight, total cement content and free W/C completely determine the NLWA concrete system in hardened state.

The 7- day compressive strength level of NLWA concretes is very close to 28- day strength for a wide range of compositions used. The average value of the 7- day compressive strength was found as 84% of the 28- day strength. No difference between the 28 and 90 days compressive strength was found, except some mixtures with decreased 90- day strength value. The scatter of some of the experimental results can be explaining by the high sensitivity of lightweight aggregate concrete to moisture content [2].

Fig. 8 and 9 demonstrate the 7 and 90 days compressive strength of NLWA concretes as a function of free W/C.

Splitting Tensile Strength

The 28- day splitting tensile strength of investigated NLWA concretes has varied from 2.1 to 5.5 MPa at compressive strength 33.0 and 53.0 MPa respectively. The relationship between the splitting tensile and compressive strength of NLWA concretes is shown in Fig. 10.

Modulus of Elasticity

The modulus of elasticity values of NLWA concretes has ranged from 17.1 to 28.9 GPa for compressive strength 38.6 and 53.0 MPa respectively. The relationship between the modulus of elasticity and compressive strength of NLWA concretes is presented in Fig. 11.

Poisson's Ratio

The Poisson's ratios of NLWA concretes were from 0.12 to 0.25 at compressive strength of 38.6 and 52.0 MPa, respectively. The relationship between the Poisson's ratio and compressive strength of NLWA concretes is presented in Fig. 12.

HEAT INSULATION PROPERTIES

Dry Unit Weight

The dry unit weight of NLWA concretes investigated was in the range of 1539 to 2105 kg/m^3. It was found that the dry unit weight of NLWA concretes has direct dependence on total cement content and compressive strength as per Fig. 7 and 13.

The dry unit weight of NLWA concretes can be presented as function of fine aggregate factor to NLWA ratio for tuff and pumice as per Fig. 14.

Thermal Conductivity

It was found that the thermal conductivity of NLWA concretes can be represented as a function of a dry unit weight. For structural NLWA concretes, thermal conductivity ranged from 0.48 to 0.62 W/m^{2}K as shown in Fig. 15.

PROPOSED CONCRETE MIXTURE PROPORTIONING METHOD

Mathematical equations based on regression analyses of the experimental results were obtained. The equations and trendlines are placed in the corresponding graphs and each data point is the average of 3 specimens value. The equations can be used for proportioning and optimising the concrete mixtures for designed unit weight and compressive strength.

One possible concrete mixture proportioning method based on the equations presented is summarised in Table 3. Column "Steps" provides step-by-step procedure for the mixture proportioning and column "Equation" gives the required equation number for each step.

The specific gravity factor method was used after the main parameters of concrete mixture have been determined.

CONCLUSIONS

The main objective of this research program was to provide behaviour prediction for structural NLWA concrete.

Based on the results of this investigation, the following conclusions were drawn:

1. Bleeding and plastic shrinkage of the NLWA concretes with silica fume and superplasticizer are very low under the normal conditions. The reduction of the setting time can be avoided by using saturated NLWA and increased superplasticizer dosage.
2. High strength structural NLWA concrete can be obtained with natural tuff and pumice. The basic rules determining of the NLWA concrete behaviour can be applied for different types of NLWA.
3. The usage of optimal amount of silica fume and superplasticizer improve compressive strength, splitting tensile strength and modulus of elasticity, significantly.
4. The blended cement containing 15% of trass or normal portland cement can be used for high strength NLWA concretes.
5. The relationship between compressive strength, dry unit weight, total cement content and free W/C completely determine the NLWA concrete system composition and properties in the hardened state.
6. It was confirmed that the thermal conductivity of NLWA concretes is a function of dry unit weight. For structural NLWA concretes thermal conductivity can be adjusted within the 0.48 to 0.62 W/m^2K.
7. Mathematical equations based on processing of experimental results are applicable for optimising concrete mixtures for designed unit weight and compressive strength.

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TABLE 1—PROPERTIES OF NLWA

NLWA Properties	*NLWA Type*				
	T1	*P1*	*P2*	*P3*	*P4*
Bulk Specific Gravity, *kg/m*^{3}	825	640	870	670	677
Specific Gravity Factor	2.15	1.06	1.09	1.37	1.39
Water Absorption, *%*					
1- Hour	19	19	20	20	20
24- Hour	22	24	30	30	22
Los Angeles Factor (ASTM), *%*	38.0	41.8	37.8	37.0	36.8

TABLE 2—PHYSICAL PROPERTIES AND CHEMICAL ANALYSIS OF BINDER MATERIALS

	Normal Cement	*Blended Cement*	*Silica Fume*
Physical Properties			
Blaine Surface Area, m^2/kg	341	338	20000
Specific Gravity, kg/m^3	3.15	3.01	2.25
Setting Time, hr_m			
- Initial	2_10	-	
- Final	2_40	-	
Compressive Strength, MPa			
- 2 days	23.7	15.9	
- 7 days	42.2	29.1	
- 28 days	55.0	40.5	
Chemical Analysis			
SiO_2	19.80	25.98	90.00
Al_2O_3	5.61	7.10	0.40
Fe_2O_3	3.42	3.36	0.36
CaO	62.97	53.71	1.63
MgO	1.81	1.68	1.02
SO_3	2.86	2.80	0.44
Na_2O	0.47	0.87	0.50
K_2O	0.87	1.10	2.28
Loss of Ignition	0.36	2.65	3.03

TABLE 3—THE NLWA CONCRETE MIXTURE PROPORTIONS

Steps	Equation	Mixture Proportions	NLWA Type				
			T1	*P1*	*P2*	*P3*	*P4*
7	-	Cement, *kg/m³*	519	498	474	446	406
5	5	Silica Fume, *kg/m³*	74	71	68	64	58
4	6	Total Binder, *kg/m³*	593	569	542	510	464
6	-	Superplastisizer, *kg/m³*	7.4	7.1	6.8	6.4	5.8
12	-	Total Water, *kg/m³*	276	226	246	257	263
9	-	NLWA, *kg/m³*	566	241	327	366	430
10	-	Fine Aggregate, *kg/m³*	679	940	709	799	708
11	-	Absorbed Water, *kg/m³*	121	65	80	89	100
3	4	Free W/C	0.262	0.284	0.307	0.329	0.350
8	14	Fine to NLWA Ratio	0.572	1.442	1.090	0.844	0.644
		Fresh Properties					
-	-	Slump, *cm*	5.5	5.5	5.5	5.5	5.5
-	1	VB, *s*	4	4	4	4	4
13	3	Fresh Unit Weight, *kg/m³*	2155	2092	2037	1990	1952
-	-	Air Content, *%*	2	2	2	2	2
		Mechanical Properties					
		Compressive Strength, *MPa*					
13	8	- 7 days	36.4	33.5	31.0	28.9	27.3
2	7	- 28 days	45.6	42.4	39.4	36.5	33.8
14	9	- 90 days	42.3	38.8	35.9	33.6	31.8
15	10	Splitting Tensile Strength, *MPa*	3.1	2.7	2.4	2.2	2.0
16	11	Modulus of Elasticity, *GPa*	24.0	22.8	21.6	20.5	19.5
17	12	Poisson's Ratio	0.207	0.180	0.164	0.157	0.158
		Heat Insulation Properties					
1	-	Dry Unit Weight, *kg/m³*	1950	1900	1850	1800	1750
19	15	Thermal Conductivity, *W/m²K*	0.582	0.564	0.546	0.530	0.514

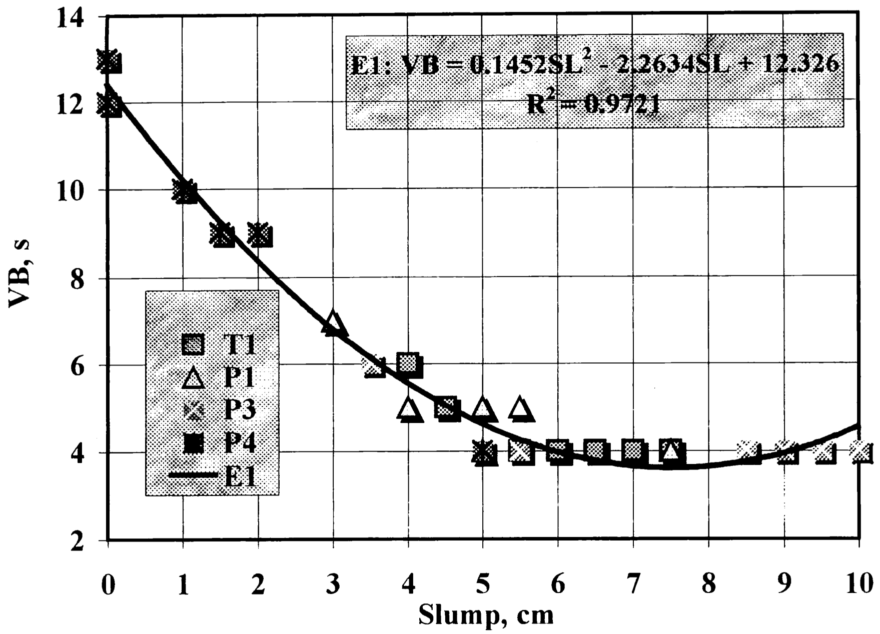

Fig. 1—Relationship between slump and VB value

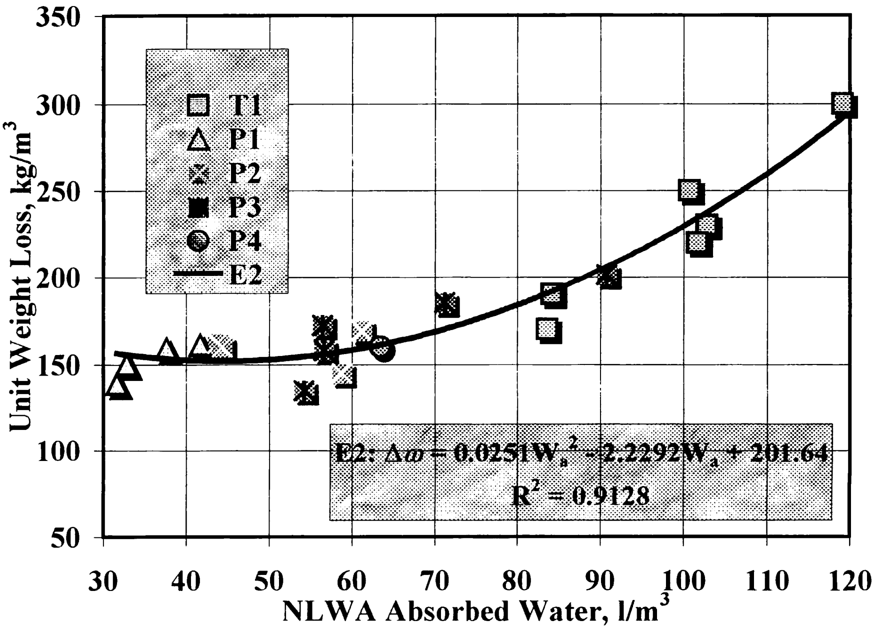

Fig. 2—Unit weight loss of NLWA concrete

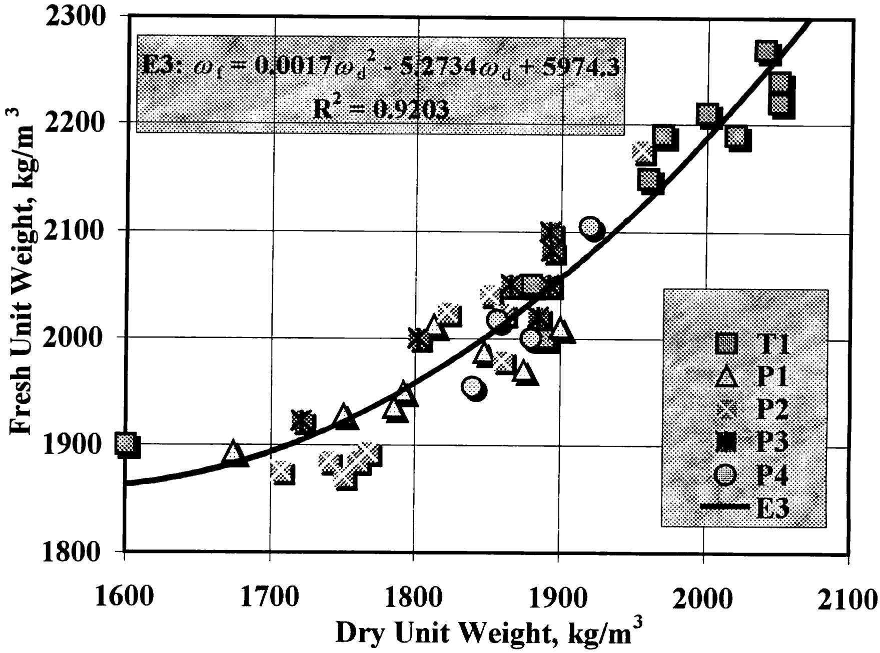

Fig. 3—Fresh unit weight of NLWA concrete

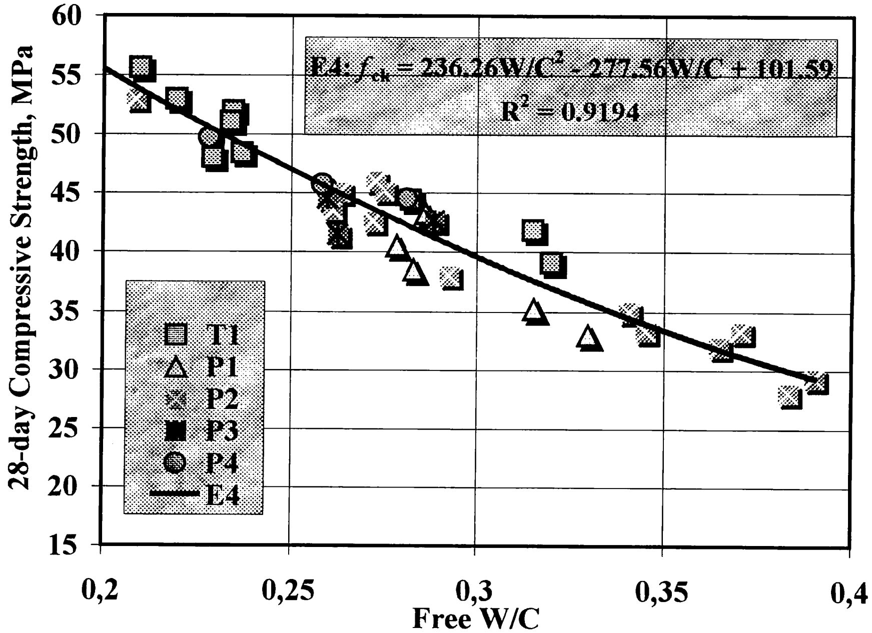

Fig. 4—28-day compressive strength of NLWA concrete

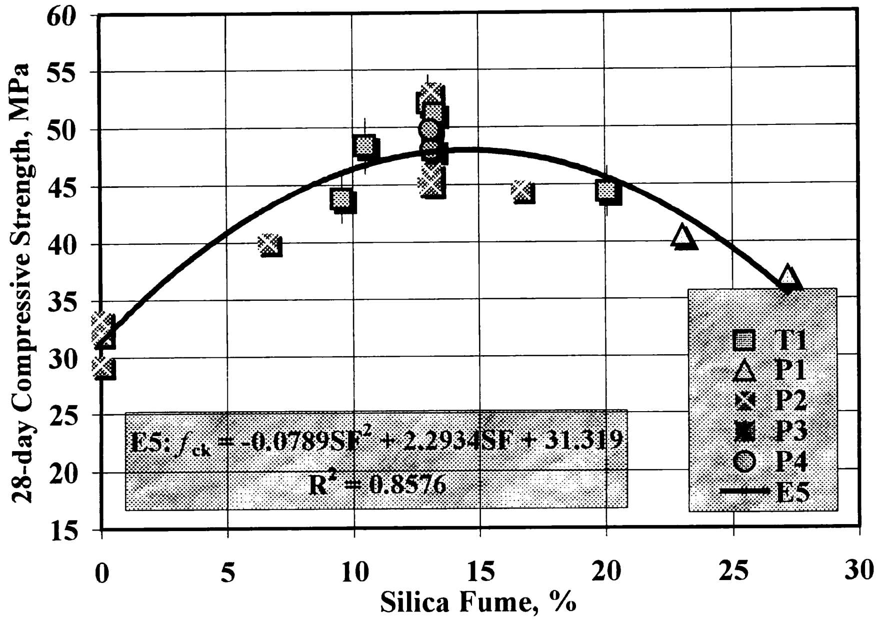

Fig. 5—The optimal amount of silica fume

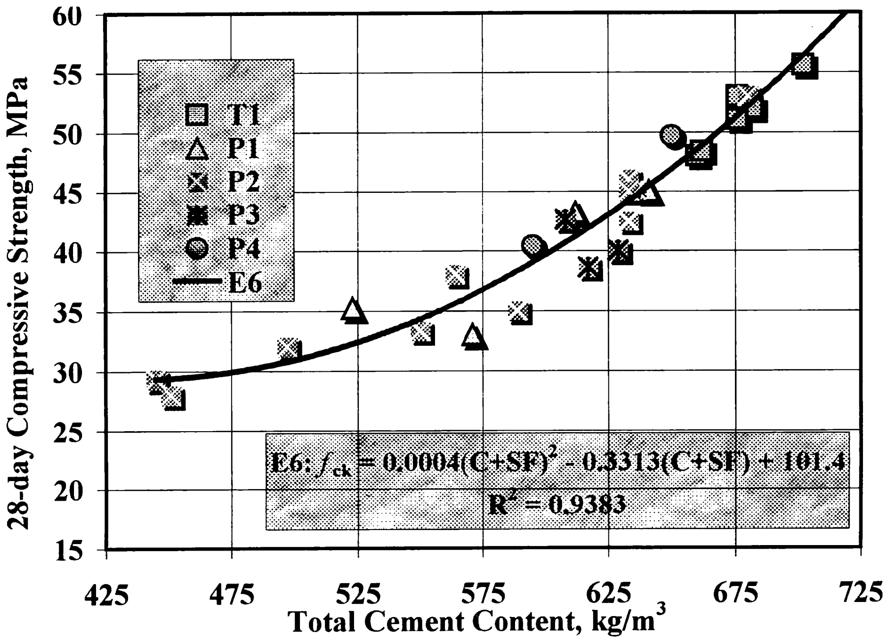

Fig. 6—Cement content effect on compressive strength

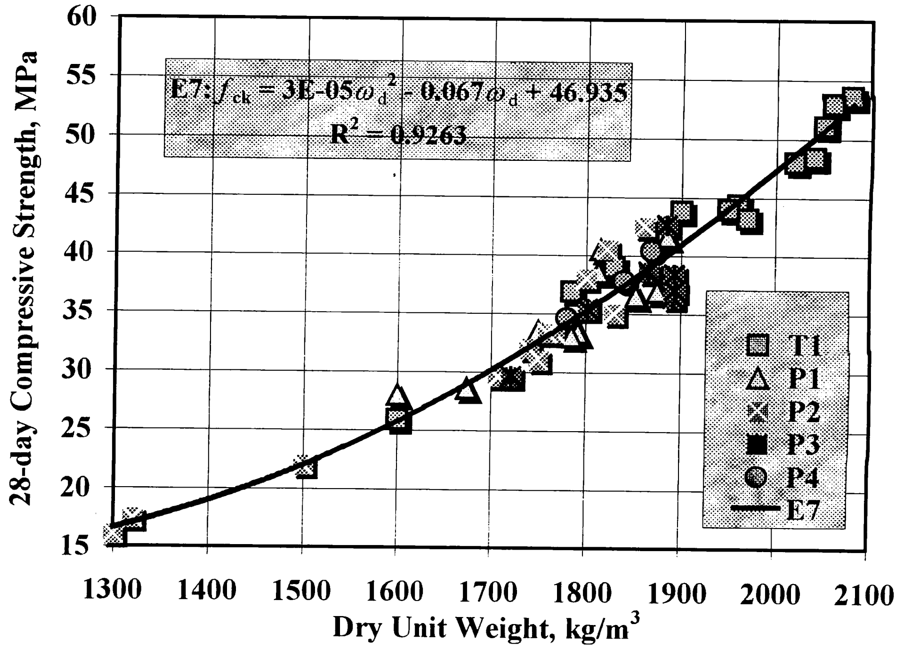

Fig. 7—Compressive strength via dry unit weight

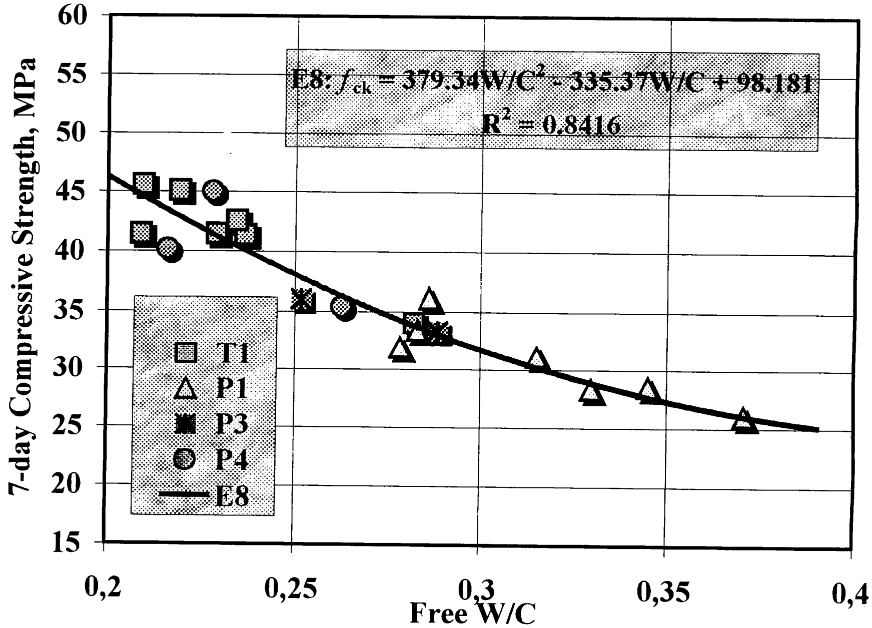

Fig. 8—Compressive strength as a function of free W/C

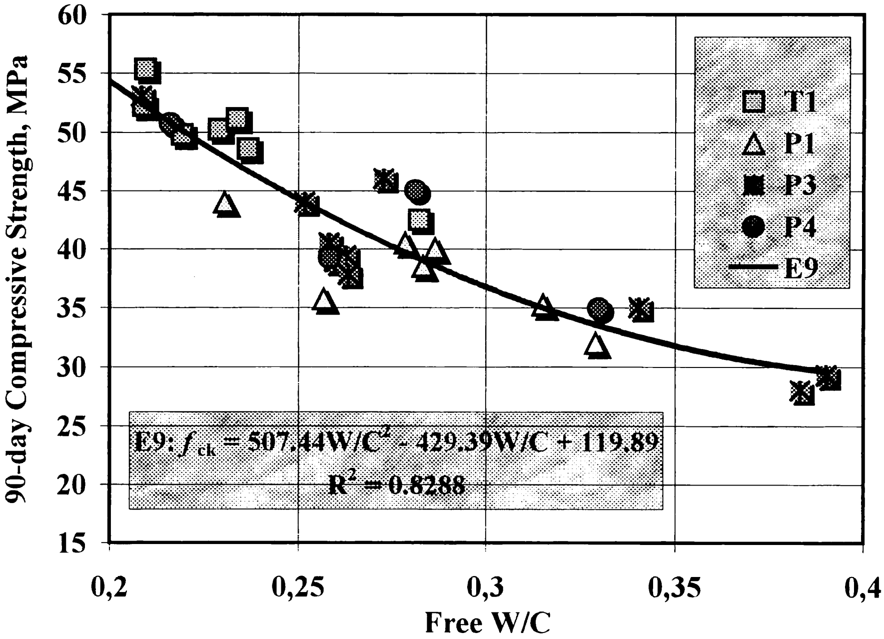

Fig. 9—Compressive strength as a function of free W/C

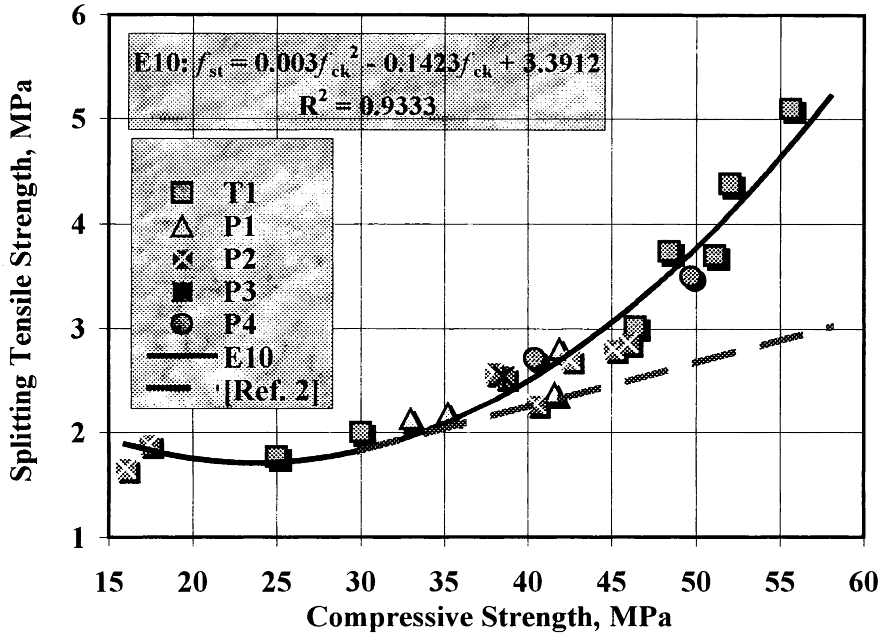

Fig. 10—Splitting tensile strength

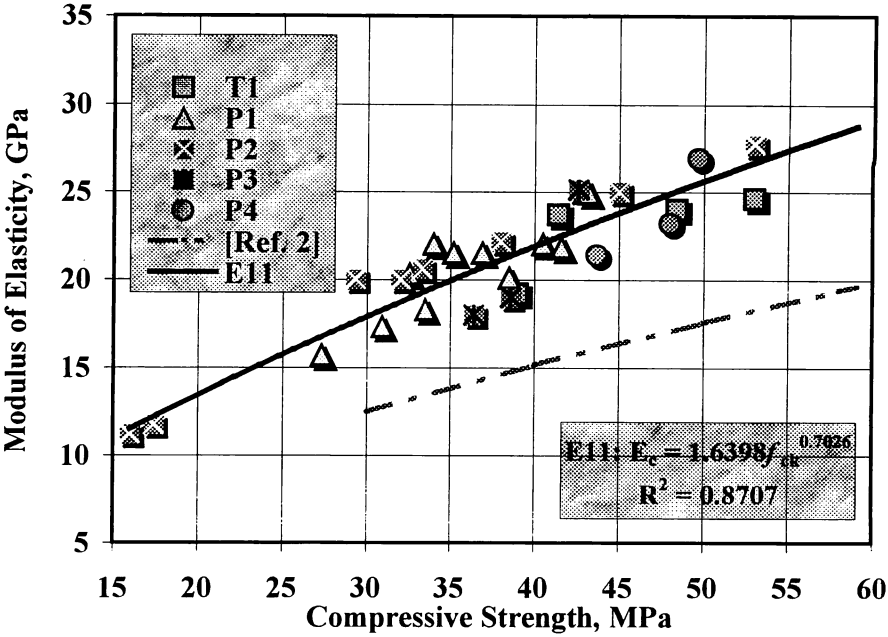

Fig. 11—Modulus of elasticity in NLWA concrete

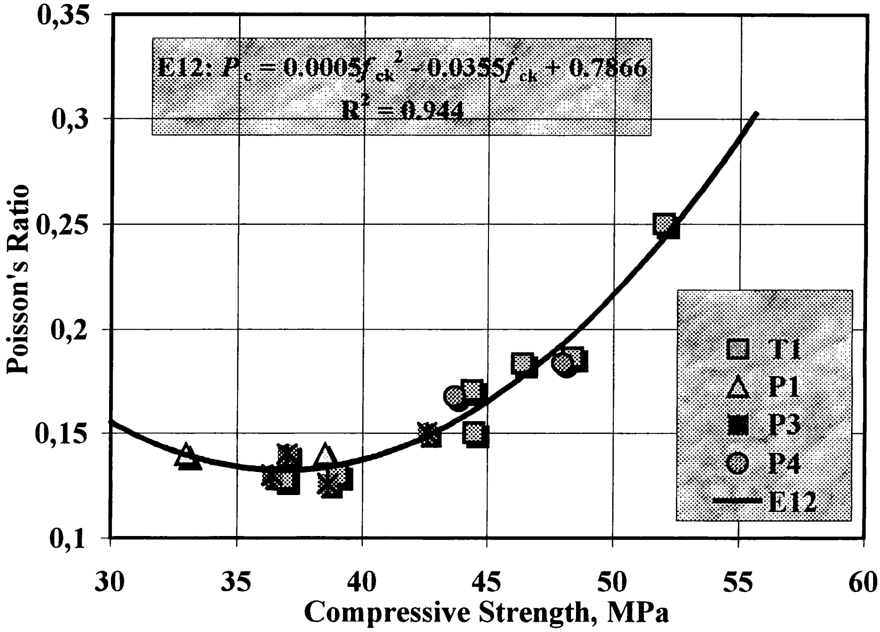

Fig. 12—Poisson's ratio of NLWA concrete

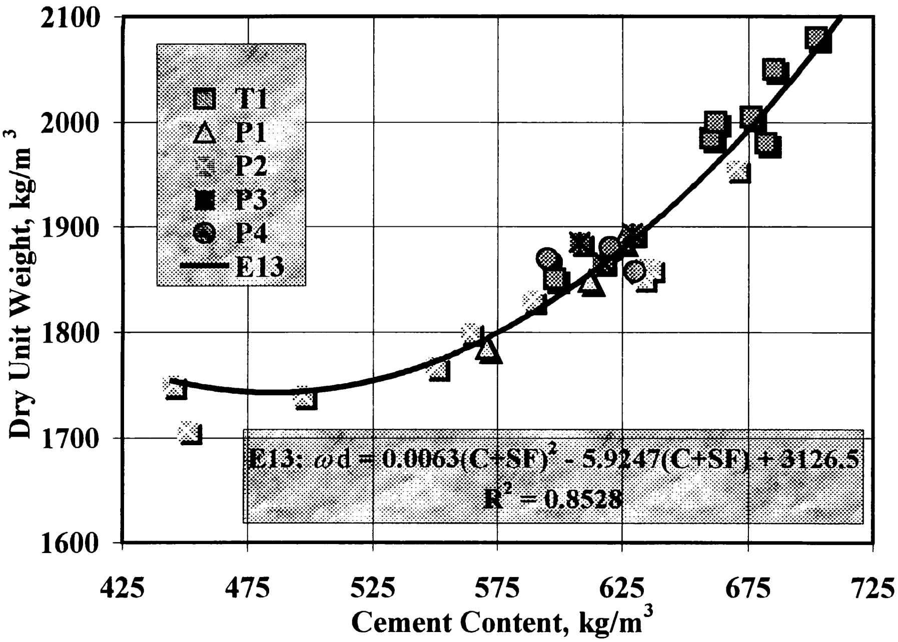

Fig. 13—Dry unit weight via cement content

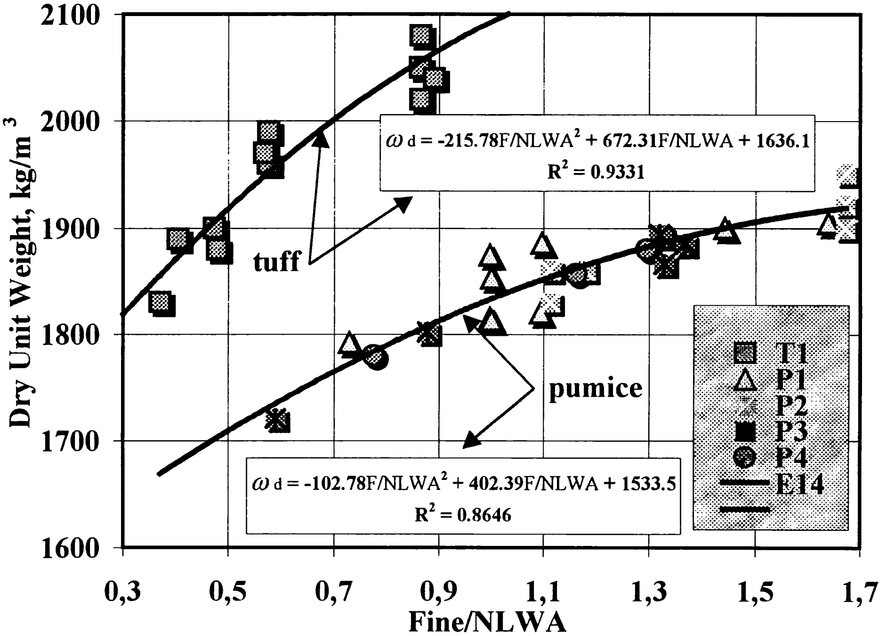

Fig. 14—Dry unit weight via fine to NLWA ratio

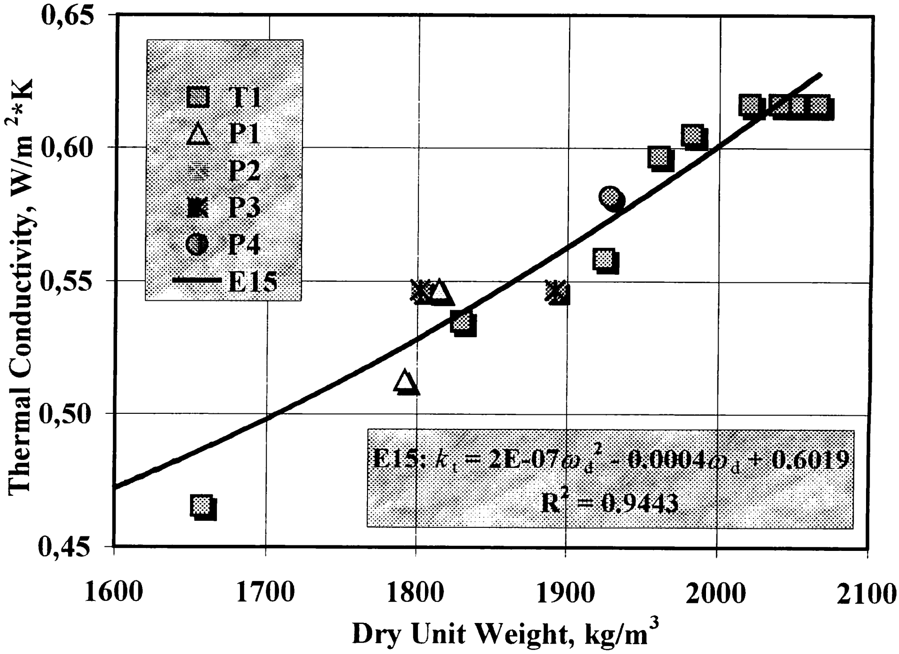

Fig. 15—Thermal conductivity of NLWA concrete