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Mechanical properties of concrete elaborated with igneous aggregates

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Abstract

Intrusive and extrusive igneous stones are natural sources of aggregates in volcanic regions. This article describes the mechanical properties of concrete elaborated with these two types of coarse aggregates. Portland cement Type I was used to prepare four different admixtures: two with crushed intrusive volcanic gravel, one with and the other without accelerating additive; and two with extrusive volcanic gravel, one with and the other without superplasticizer additive. The four admixtures, cured on a saturated bed of sand, had a slump of 100 mm. Tests of compressive strength, splitting tensile strength, modulus of rupture and dynamical elastic modulus were performed on the concrete specimens at ages of 3, 7, 14, 21, 28 and 45 days. All of these concretes proved to possess excellent mechanical behavior. This is important because it means that it is possible to lower the overall cost of concrete by using cheap and abundant aggregates. © 2002 Elsevier Science Ltd. All rights reserved.

Keywords: Compressive strength; Flexural strength; Tensile strength; Dynamic elastic modulus; Igneous aggregates

1. Introduction

One of the main requirements of hydraulic concrete is its capacity to resist compression; therefore, one tries to maximize the mechanical resistance of a given concrete structure using raw materials with the lowest cost for a given region [1]. The interfacial transition zone (ITZ) of concrete, a thin layer up to 50 μm wide between the bulk of the hydrated cement paste and the irregularly shaped aggregate particles, plays a key role in the final values of durability and mechanical properties of the concrete composite [2]. The ITZ, characterized by a higher porosity with respect to the bulk cement paste [3,4], depends on the mineralogy and texture of the coarse aggregate [5]. In turn, the formation of microcracks in the ITZ explains the dependence of the mechanical properties of concrete on the type of coarse aggregates used for its elaboration [6]. For this reason, in the preparation of high-quality concrete, it is important to use coarse aggregates which, in addition to providing high mechanical resistance, are abundant and inexpensive in the surroundings of a given region. Intrusive and extrusive igneous rocks satisfy this requirement in Central–Western Mexico and, therefore, they are a natural source of aggregates in the region. Although they are already described in ASTM C 294-98 [7], there are no systematic studies on the mechanical properties of hydraulic concrete elaborated with these types of volcanic aggregates reported in the literature. This article reports on the mechanical properties of concrete samples elaborated with these two types of igneous rocks of volcanic origin used as coarse aggregates.

2. Experimental procedure

2.1. Materials

We used Portland cement Type I which was checked to conform to ASTM C 150 with a wide margin. The aggregates used were from the Volcanic Belt, in Central–Western Mexico. We used two types of coarse aggregates: extrusive volcanic gravel of natural size up to 1 in. and crushed intrusive volcanic gravel of size up to 3/4 in. Extrusive igneous rocks are andesitic pyroclastic products composed mainly of volcanic glasses with less than 56 wt.% silica

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Table 1
Characterization of aggregates

Test	Volcanic sand	Volcanic gravel	Crushed basalt gravel
Bulk-specific gravity ASTM C 127-93	2.41	2.62	2.62
Absorption (%) ASTM C 127-93	2.55	5.31	3.48
Bulk density and voids (kg/cm^3) ASTM C 29-97	1.305	1.120	1.376
Bulk density and voids (kg/cm^3) ASTM C 29-97	1.376	1.235	1.472
Sieve analysis ASTM C 136-96	Fineness modulus, 3.58	Maximum size, 1 in.	Maximum size, 3/4 in.

contents and almost no crystals immersed in their matrixes [8]. Intrusive crushed aggregates are harder basalts richer in crystals immersed in their glass matrixes, which contain less than 50 wt.% silica. As fine aggregate, we used volcanic sand with a composition similar to that of extrusive igneous rocks. Table 1 shows a set of physical properties of the aggregate materials. On two of the four admixtures, we used water-reducing (superplasticizer) and -accelerating additives, both described in ASTM C 494-99 Types A and C.

From Table 1, we see that the water absorption percentage of the extrusive volcanic gravel, 5.31%, is greater than the maximum value, 4%, recommended by ASTM C 127-88/93. Likewise, the fineness modulus of the sand used, 3.58, is greater than the maximum value, 3.1, recommended by ASTM C 33-99. The sieve analysis of the aggregates revealed that none of the two types of coarse aggregates used in our study satisfies ASTM C 136-96 in a perfect way. However, as we will show later, the concrete specimens elaborated with these aggregates showed excellent mechanical behavior with age, and, in particular, they exceeded the design value for compressive strength in all cases.

2.2. Preparation of specimens

We prepared four different admixtures: two with crushed intrusive volcanic gravel, one with and the other without accelerating additive; and two with extrusive volcanic gravel, one with and the other without superplasticizer additive. In all cases, we used Portland cement Type I and fine aggregate of extrusive volcanic origin. The detailed amounts of materials used are shown in Table 2. The four admixtures were designed according to the American Concrete Institute Method ACI 318 [9]; this method gives rise to more workable admixtures and allows greater values for the w/c ratio than the 0.44 originally proposed by Abrams [10] back in 1918. The w/c ratio used for the three concrete admixtures without superplasticizer was 0.57, while the w/c ratio for the admixture with superplasticizer was 10% lower. The projected mean value for the compressive strength of all the concretes was 250 kg/cm^2 with a standard deviation lower or equal to 30 kg/cm^2. The workability of the admixtures was measured according to ASTM C 143-98, providing slump values of 100 mm in all cases.

Coarse and fine aggregates were mixed with cement first, and then water and additives (the latter for only two of the admixtures) were added into a stationary turbine mixer for a total of 12–15 min. The four admixtures were cured on a saturated bed of sand covered with a plastic sheet to avoid evaporation, according to ASTM C 31-98; they were prepared in wintertime to minimize systematic errors due to moisture absorption. As evidenced by the results shown later, this curing procedure provides good hydration [11–13]. The concrete used to elaborate the specimens was sampled according to ASTM C 183. All the specimens were removed from their steel moulds at 24 h.

The total number of concrete specimens elaborated for this study was 896. A total of 160 cylindrical specimens 15 cm diameter and 30 cm high, capped with a layer of melted sulfur as described in ASTM C 617-98, were elaborated according to ASTM C 31-98 for each of the four admixtures to measure compressive and tensile strengths. Likewise, a total of 64 bars, $15 \times 15 \times 60$ cm, were elaborated for each of the four admixtures to measure modulus of rupture and dynamical elastic modulus [14,15].

2.3. Mechanical tests

The mechanical tests performed on the concrete specimens, at ages of 3, 7, 14, 21, 28 and 45 days, were compressive strength, splitting tensile strength, modulus of

Table 2
Mixture proportions and slump of fresh concrete

Mixture	Design method	w/c ratio	Cement (kg/m^3)	Fine aggregates (kg/m^3)	Coarse aggregates (kg/m^3)	Slump (mm)	Additive (l/m^3)
Crushed basalt gravel	ACI	0.57	350	877	826	100	0.0
Volcanic gravel	ACI	0.57	350	799	768	100	0.0
Crushed basalt gravel with accelerating additive	ACI	0.57	350	877	826	100	1.4 accelerating
Volcanic gravel with superplasticizer	ACI	0.52	350	765	750	100	1.4 superplasticizer

rupture and dynamical elastic modulus. The first three were measured according to ASTM C 39-99, ASTM C 496-96 and ASTM C 78-94, respectively, by using a universal test machine (Forney model LT1150) with capacity of 150 tons and steps of 1–5 kg. Dynamical elastic modulus [12,13] was measured by the nondestructive impulse excitation technique (Grindo-Sonic System); this method is based on the excitation of a homogeneous test sample by means of a light mechanical impulse. The resulting vibration, which depends on the nature, geometry and mass of the material, is picked up and analyzed by the instrument to select and measure the fundamental mode of oscillation. This instrument meets ASTM C 215-97 and provides the value of the dynamical elastic modulus once the density and geometrical dimensions of the sample are specified.

3. Results and discussion

Fig. 1 shows the results for compressive strengths at different ages as measured on the four types of concrete admixtures studied. The error bars reflect the 4% S.D. of the measurements on the various specimens. We tested 10 specimens at 3, 7, 14 and 21 days and 20 at 28 and 45 days for each of the four concrete types. In all cases, the design value (250 kg/cm^2) was obtained earlier than 20 days and an asymptotic value greater than 300 kg/cm^2 was obtained for ages older than 28 days. The best results were obtained for volcanic gravel with superplasticizer additive. At early ages, the effect of the accelerating additive on the compressive strength of the concrete elaborated with crushed basalt gravel was significant: at 3 days, the concrete made with accelerating additive had 73% of the final value, while the concrete without accelerating additive had reached only 56% of the final value. On the other side, the superplasticizer additive gave rise to an improvement of 14% on the compressive strength of the concrete elaborated with volcanic gravel. The mechanical properties of the two concretes without additives were quantitatively similar: the one made with volcanic gravel had slightly higher values at early ages than the one made with crushed basalt gravel, while the difference between the two was marginal for the mature specimens.

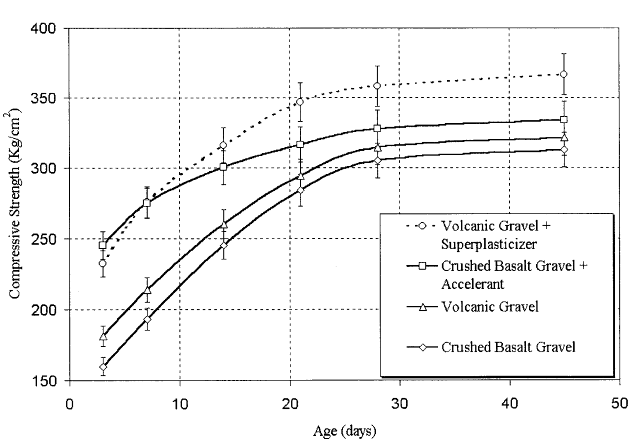

Fig. 1. Results for compressive strengths at different ages.

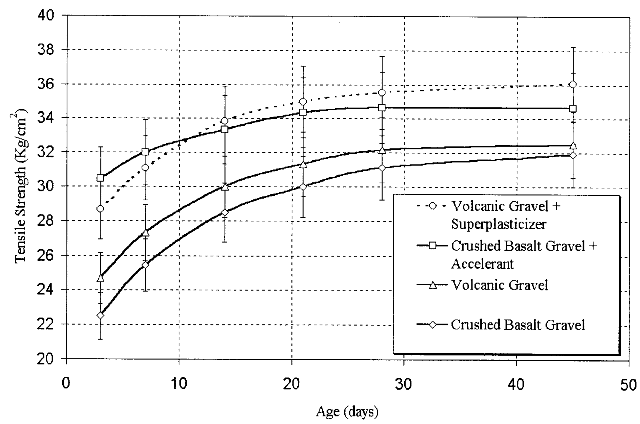

Fig. 2. Results for splitting tensile strength at different ages.

Fig. 2 shows the results for tensile strengths at different ages as measured on the four types of concrete admixtures studied. The error bars reflect the 6% S.D. of the measurements on the various specimens. The number of specimens tested was 10 at 3, 7, 14 and 21 days and 20 at 28 and 45 days for each of the four concrete types. All of the 320 cylindrical specimens failed along the middle axial line. The best results were obtained for volcanic gravel with superplasticizer. The effect of the additives was significant — for the concretes elaborated with crushed basalt gravel, the improvement due to the accelerating additive was 35% at 3 days and 9% at 45 days. The improvement due to the superplasticizer on the concrete made with volcanic gravel was 16% at 3 days and 11% at 45 days. In all cases, the tensile strength values, f_T, of the mature concretes correlate well with the values for compressive strength, f_c'. The linear correlation can be expressed as $f_T = 0.10 f_c'$.

Fig. 3 shows the results for the modulus of rupture at different ages as measured on the four types of concrete admixtures. As expected, the totality of the 128 beam specimens failed in the middle third. The error bars reflect the 5% S.D. of the measurements on the various specimens. We tested three specimens at 3, 7, 14 and 21 days and 10 at 28 and 45 days for each of the four concrete types. As in the previous two figures, the best results were obtained for volcanic gravel with superplasticizer. The effect of the additives was also significant: the concrete elaborated with crushed basalt gravel and accelerating additive had its modulus of rupture 50% higher at 3 days and 10% higher at 45 days with respect to the same concrete without accelerating additive; likewise, the improvement due to the water-reducing additive on the concrete made with volcanic gravel was 26% at 3 day and 14% at 45 days. As in the case of the tensile strength, the moduli of rupture, M_R, of the mature concretes correlate well with the values for compressive strength,

f_c'. The linear correlation in this case can be expressed as $M_R = 0.12f_c'$.

Fig. 4 shows the results for the dynamic elastic modulus at different ages as measured on the four types of concrete admixtures. The error bars reflect the 1% S.D. of the measurements on the various specimens. The number of specimens tested was 3 at 3, 7, 14 and 21 days and 10 at 28 and 45 days for each of the four concrete types. As in the three previous figures, the best results were obtained for volcanic gravel with superplasticizer. The accelerating additive had a significant effect on the concrete elaborated with crushed basalt gravel mainly at early ages: the improvement was 14% at 3 days and 3% at 45 days. The concrete made with volcanic gravel and superplasticizer showed a value 6% higher at 3 days and 4% at 45 days. In all four cases, the dynamic elastic moduli, E_d, of the mature concretes correlate well with the corresponding values for compressive strength. In this case, however, the correlation is expressed better through the square root of f_c' as follows: $E_d = 17{,}700f_c'$.

Through this empirical result, one can indirectly obtain the value of compressive strength by means of the much simpler measurement of the dynamic elastic modulus; the latter has the additional advantage of being a nondestructive test that can be performed in situ [13]. The high values obtained for the dynamic elastic modulus of concrete elaborated with intrusive and extrusive aggregates of volcanic origin provide additional resistance to structures constructed with this type of concrete in seismic regions, which are usually volcanic zones as well.

As shown in Figs. 1–4, the values of the mechanical properties studied on the concrete samples possessed the expected time behavior: they increased with time significantly up to ages of 21 days while the increments were less significant from 21 to 45 days. Even though the fineness modulus of the sand used, 3.58, was outside the recommended range, 2.3–3.1, and the water absorption percentage of the volcanic gravel, 5.3%, was greater than the maximum recommended value, 4%, the concrete elaborated with these materials with a w/c ratio of 0.57 had an excellent mechanical behavior and good workability. The use of a small amount of superplasticizer additive allowed a reduction of the w/c ratio to 0.52 while keeping the slump at the same value of 100 mm and giving rise to better mechanical properties.

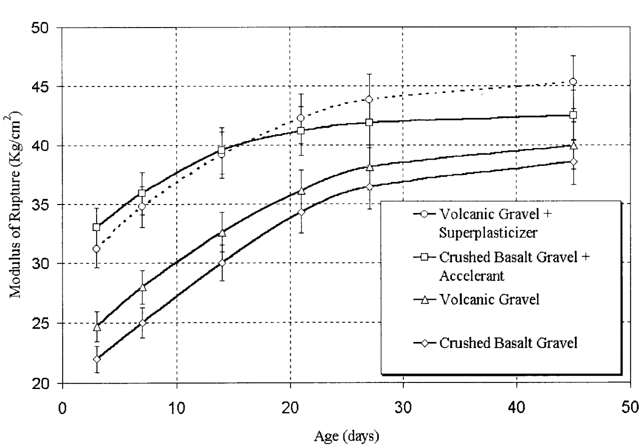

Fig. 3. Results for modulus of rupture at different ages.

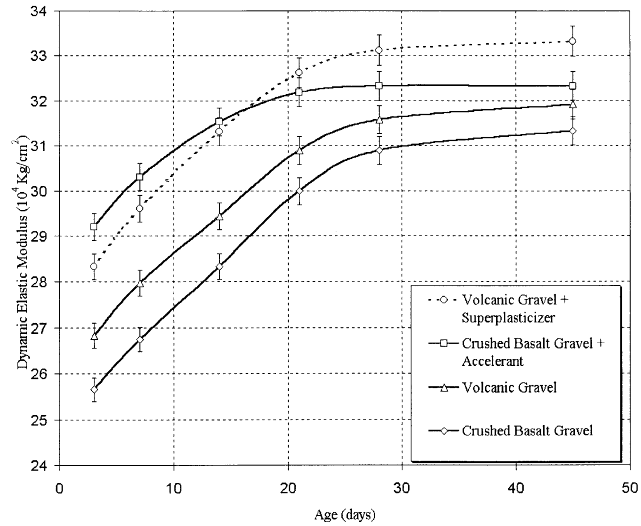

Fig. 4. Results for dynamical elastic modulus at different ages.

The slightly lower values for the mechanical constants of concrete elaborated with crushed basalt gravel with respect to the one made with volcanic gravel can be attributed to the excess of powder particles produced during the crushing process, which did not include water flushing to remove powder: these powder particles presumably remain adhered to the walls of the bigger gravel particles, giving rise to a wider and weaker interfacial zone. Along the same argument, the higher porosity of the extrusive volcanic gravel with respect to crushed basalt may also explain the slightly better strength of the concrete elaborated with the former aggregate due to the greater absorption of cement paste giving rise to a stronger interfacial zone.

4. Conclusions

The following conclusions can be drawn from this study.

(1) Concretes elaborated with crushed intrusive and extrusive volcanic gravel as coarse aggregates have been shown to possess mechanical properties with excellent behavior: the design value for compressive strength, 250 kg/cm^2, was obtained with a margin of at least 25% with an excellent slump value of 100 mm. This is important because it means that it is possible to lower the overall cost of concrete by using cheap and abundant aggregate materials.

(2) The best values for compressive strength, tensile strength, modulus of rupture and dynamic elastic modulus were obtained for the concrete specimens elaborated with volcanic gravel and a small amount of superplasticizer

additive; the use of the latter affected concrete in a positive manner by altering its rheology and allowed a 10% reduction of the w/c ratio without affecting the workability of the admixture. In addition, the use of this additive improved the mechanical properties of the concrete elaborated with extrusive volcanic gravel with respect to the same concrete made without additive in the following way: compressive strength 14%, tensile strength 11%, modulus of rupture 14% and dynamic elastic modulus 4%.

(3) The effect of the accelerating additive on the mechanical properties of the concrete elaborated with crushed basalt gravel was significant: at 3 days, the concrete made with accelerating additive had 73% of the final value, while the concrete without additive had reached only 56% of the final value.

(4) The dynamic elastic moduli, E_d, of the mature concretes were found to correlate with compressive strength, f_c', as $E_d = 17{,}700 f_c'$. This result can be used to indirectly obtain the compressive strength of a sample by knowing its dynamic elastic modulus; the latter has the advantages of being obtained by means of a nondestructive test that can be performed in situ in a much simpler way. In turn, once f_c' is known, values for tensile strength and modulus of rupture can be estimated through the linear correlations: $f_T = 0.10 f_c'$ and $M_R = 0.12 f_c'$.

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