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Full Length Research Paper

Effect of low quality aggregates on the mechanical properties of lightweight concrete

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Ignimbrite is one of the pyroclastic volcanic rock formations. Its soundness, lightness and shape workability are the most advantageous properties. These properties get its usage since prehistoric ages as construction materials, like bricks and caves. This kind of pyroclastic volcanic rock exists all over the world, particularly in volcanic and high seismicity provinces. Some physical and mechanical properties of ignimbrite rock samples are obtained in order to interpret influence of aggregate strength on concrete produced and for comparing with other lightweight aggregate concretes. The ignimbrite and pumice are used as crushed aggregate in the present work. The aggregate concentration of concrete specimens is designed in four different groups by using 0, 25, 50, 75 and 100% ignimbrite and pumice, as a proportion of aggregate volume with the same water cement ratio of 0.6 and the dosage of 300 kg/m^3 lightweight concrete manufactured. All concrete specimen groups are settled in steel formworks and water cured for 7, 14 and 28 days. According to the pumice and perlite like lightweight concretes, the ignimbrite concretes had higher strength. So, its usage as a construction material like lightweight concrete, brick or panel is more advantageous in producing cheap anti-seismic constructions. Therefore, ignimbrite concretes lighter the building, get less earthquake loads and behave better than gas, pumice or perlite concrete. Another advantage of ignimbrite is its occurrence in active fault zones (earthquake areas) all over the world.

Keywords: Ignimbrite, pumice, lightweight concrete, compressive strength, splitting tensile strength.

INTRODUCTION

Concrete is exceedingly a multiphase complex heterogeneous material and one of the principal materials for structures. However, the heterogeneous structure of concrete results in some undesirable effects. The heterogeneity and properties of concrete are mostly concerned with hydration. Hydration, the chemical reaction between water and the ingredients of cement is one of the most important properties of its strength gaining process. This property of hydration caused the volume change of hydrated cement and varying hydration rate through the concrete and time dependency of strength gain. One of the main reasons of strength gain is the mechanical properties of concrete. The mechanical properties of cement based materials is needed by designers for stiffness and deflection evaluation and is a fundamental property required for the proper modelling of its constitutive behavior and use in various structural applications.

For this reason, determination of mechanical properties of concrete has become very important from a design point of view. But due to the economic considerations, there is a strong demand on natural resource usage. Moreover, when weights of the structures are considered, not only natural light weight aggregates, but also, artificial light materials, like gas concrete are used. Incorporation of natural/artificial resources in concrete, leads to environmental, economic and/or technological benefits (Gül et al., 2007; Aydın et al., 2007; Aydın, 2007; Aydın and Gül, 2007; Aydın et al., 2006; Düzgün et al., 2005; Tortum et al., 2005; Oğuz and Aydın, 2003).

A composite material can be defined as a combination of at least two different materials. Usually, the properties of multiphase composite have different properties of the original components. It is appropriate to consider concrete as a cement-based composite, which consists of

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aggregate, embedded in a matrix of hydrated cement paste (Yang, 1997).

Aggregates generally constitute about 50 to 80 % of concrete volume. Due to its large volume fraction in concrete, it exerts a major influence on the properties of concrete (Mindess et al., 1981; Chi et al., 2003). The influence of its characteristics on the quality of concrete has also been worked on by many researchers (Chi et al., 2003; Giaccio et al., 1992; Baalbaki et al., 1991; Nilsen et al., 1995). The importance of the mineralogical characteristics of coarse aggregate on the properties of concrete has been pointed out by Baalbaki et al. (1991), Giaccio et al. (1992) and Mindess et al. (1981). In conventional concrete, the properties of coarse aggregates seldom become strength-limiting as the weakest components in this type of concrete mixtures ate the quality of hardened cement paste and the transition zone between the cement paste and the coarse aggregates, rather than the coarse aggregates themselves (Mehta, 1986; Yuan and Guo, 1987; Kaplan, 1959; Larrard and Belloc, 1992; Zia, 1994; Almusallam et al., 2004).

Due to the rapid economic development and growth in the world population, there is a strong demand on natural aggregate usage. Such aggregates are available in many parts of the world and can be used in producing concrete in a wide range of unit weights and suitable strength values for different fields of applications (Neville, 1988; Demirboğa et al., 2001). The aim of conventional concrete technology is its maximized mechanical performance improvement using raw materials (Almusallam et al., 2004; Alonso et al., 2002; Topçu, 1997). Low quality lightweight aggregates are widespread in many parts of the world and there is a concern as to the production of high quality lightweight concrete in those regions. With a wide range of that low quality lightweight aggregates available for concrete, there is need for a better understanding of the properties influence of those aggregates on the compressive strength, splitting tensile strength and elastic modulus of concrete (Chi et al., 2003; Almusallam et al., 2004).

Ignimbrite is defined as, "a pyroclastic deposit or rock body, made predominantly from pumiceous material, which shows evidence of having been emplaced as a concentrated and hot particulate flow". The "ash-flow tuffs" and "Shirasu" deposits commonly referred to in American and Japanese literature, respectively, are comparable with ignimbrites in this sense.

These materials consist of: pumice clasts (discrete fragments of pumice), crystals, lithic clasts (fragments of country rock incorporated into the eruption sequence) and a groundmass of glass shards (ash-sized glass particles resulting from the disintegration of pumice). In general, the groundmass shards are chaotically arranged and the pumice and lithic clasts and crystals are separated by groundmass. Clast-supported ignimbrites are an exception. The strength of igneous rocks is high when the rock is composed of a dense network of interlocking crystals. Usually, it is present in the intrusive rocks which had time to develop such a pattern and the bulk rock densities are as high as 2.2-2.3 g/cm^3. Ignimbrites are of low density and high porosity, weak in compression and have low tensile strength and cohesion, yet the angle of internal friction is comparatively high. All ignimbrites undergo significant plastic deformation prior to failure. Extensive systems of open, continuous and vertical joints occur in many ignimbrites, typically forming widely a much spaced, irregular columnar pattern, while other ignimbrites are effectively non-jointed, though occasionally closed, continuous and vertical joints occur at extremely wide spacing. Large changes in strength and jointing may occur within a single profile (Moon, 1993; Schumacher and Schumacher, 1996; Ismail and Sadek, 2009).

This study was conducted to evaluate the mechanical properties of concrete prepared with two types of low quality aggregates, namely pumice and ignimbrite. In order to evaluate the influence of each aggregate type in enhancing the strength of concrete prepared with volume fractions such as 0.00, 0.25, 0.50, 0.75 and 1.00, the water cement ratio is kept constant for all types of concretes to clarify low quality aggregate type effect on the mechanical properties of concretes. It is assumed that multivariate normality and co variances are equal in groups. By the way, to the best of the author's knowledge, this is the only research on ignimbrite concretes.

EXPERIMENTAL PROGRAMME

Materials and mixture proportions

Type III cement complying with ASTM C 150 requirements was used in the preparation of concrete specimens. The ASTM D 75, ASTM C 136 and ASTM C 29 were used for sampling, grading, unit weight and fineness modulus of aggregates, respectively. The chemical composition of cement, pumice (PA) and ignimbrite (IA) are given in Table 1 and some physical and mechanical properties of Portland Cement (PC) are given in Table 2, respectively. The concrete specimens were prepared with the same water cement ratio of 0.6, dosage of 300 kg/m^3 and 0, 25, 50, 75 and 100% ratios for each aggregate type. The natural crushed gravel (CGA) was used for control specimens as the aggregate and the detailed amounts of materials used are shown in Table 3.

Preparation of specimens

The pumice aggregate and ignimbrite aggregates were not used for the same concrete mixture in this work and so, nine types of concrete were prepared with PA, IA, and CGA. The concrete specimens, 100 mm in diameter and 200 mm high, were prepared to determine the compressive and splitting tensile strength and static modulus of elasticity. The concrete constituents were mixed in a laboratory countercurrent mixer for a total of 5 min to obtain uniform consistency.

Hand compaction was used for every specimen. For each mix, three specimens were prepared. During the first 24 h, the specimens were left in the molds and were then removed and cured in lime saturated water at 20 ± 3°C until the 6th, 13th and 27th days. Prior to the tests, the specimens were removed from the curing room and left to dry in the air for 24 h. The specimens were capped

Table 1. Chemical components of PC, IA, and PA (%).

Component	PC	IA	PA
		%	
SiO_2	19.80	68.42	72.1
Fe_2O_3	3.42	3.17	1.63
Al_2O_3	5.61	13.56	13.26
CaO	62.97	4.01	1.86
MgO	1.76	2.21	0.1
SO_3	2.95	-	0.02
K_2O	0.3	3.16	4.86
TiO_2	0.2	0.39	0.17
Sulphide (S^{-2})	0.17	-	-
Chloride (Cl^-)	0.04	-	-
P_2O_5	-	0.18	-
H_2O^+	-	0.82	-
H_2O^-	-	0.43	-
Undetermined	0.30	1.72	-
Free CaO	0.71	-	-
LOI	0.36	1.93	-

Table 2. Physical and mechanical properties of PC.

Density (g/cm^3)	3.12
Specific surface (cm^2/g)	3520
Reminder on 200 µm sieve (%)	0.1
Reminder on 90 µm sieve (%)	3.1
Setting time start (min)	132
Setting time end (min)	178
Volume expansion (Le Chatelier, mm)	3
Compressive strengtgh (kg/cm^2)	
2 days	242
7 days	382
28 days	444

with a layer of melted sulfur as described in ASTM C 617 before the mechanical tests.

Mechanical tests

The mechanical tests performed on the prepared concrete specimens, at ages of 7, 14, and 28 days, were compressive and splitting tensile strength and elastic modulus in accordance with ASTM C 192, ASTM C 496 and ASTM C 469, respectively.

RESULTS AND DISCUSSION

Compressive strength

The compressive strength of concrete specimens prepared with the selected low quality and CG aggregates was determined up to 28 days of curing. Figure 1 shows the variation of compressive strength of the concrete specimens prepared with PA, IA and CGA for variably low quality aggregate ratios. As expected, the compressive strength increased with age and decreased with the aggregate ratio increase in all types of concrete specimens. After 28 days of curing, the highest compressive strength was noted in the CGA concretes and the lowest was noted in the PA concretes. Meantime, IA concretes showed greater compressive strength than PA concretes. The influences of aggregate type, ratio and age on the compressive strength of PA, IA and CGA concretes are summarized in Figures 1 - 3.

While the CGA concretes compressive strengths were 24.27, 27.46 and 32.45 MPa for 7, 14 and 28 days, the compressive strengths of concretes that is made up of 25, 50, 75 and 100% PA replacement for CGA were 17.87, 19.43, 24.07, 11.71, 13.20, 18.12, 10.63, 12.57, 15.39, 9.10, 9.63 and 13.07, respectively. Reductions in the compressive strength due to PA were 26.4, 29.2, 25.8, 51.8, 51.9, 44.2, 56.2, 54.2, 52.6, 62.5, 64.9 and 59.7% for 25, 50, 75 and 100% PA replacements, respectively. This is due to the lightness and porous structure of PA.

The IA concretes that is made up of 25, 50, 75 and 100% IA replacement for CGA were 21.51, 23.57, 30.34, 21.18, 23.20, 29.25, 21.00, 22.06, 28.12, 18.92, 20.53 and 26.15, respectively. Reductions in the compressive strength due to IA were 11.4, 14.2, 6.5, 12.7, 15.5, 9.9, 13.5, 19.7, 13.3, 22, 25.2 and 19.4% for 25, 50, 75 and 100% IA replacements, respectively. The greater density of IA than PA resulted to less decrease in compressive strength values. The detailed experimental results are given in Table 4.

These data indicate that the type of aggregate has a significant effect on the compressive strength of concrete. In such a concrete, the bulk of compressive load is borne by the aggregates rather than cement paste alone (Almusallam et al., 2004). The failure in such concrete is often through the aggregates. As the PA is known to be weaker than the IA and CGA, the low load carrying capacity of its concrete is understandable. The compressive strength of PA concrete was 17 - 52% less than that of IA concrete. This indicates that the IA produces a stronger concrete than the PA.

While the 28 day compressive strength was taken as 100%, the 7 and 14 days compressive strength for CGA, PA and IA were 75, 85, 65 - 74, 73 - 82, 71 - 75 and 78 - 92%, respectively. According to Almusallam et al. (2004), the ratio between 7, 14 and 28 days strength is like the mentioned percentages and this observation is in good agreement with that reported by Chi et al. (2003), Almusallam et al. (2004) and Alonso et al. (2002).

Splitting tensile strength

Figure 4 shows the splitting tensile strength of the concrete specimens prepared with PA, IA and CGA. The

Table 3. Mixture proportions of PA, IA and CGA concrete.

Aggregate type	Sieve size (mm)	Density (g/cm^3)	Aggregate ratio (%)				
			0	25	50	75	100
			(kg/m^3)				
Pumice	0 - 2	1.64	-	76.9	153.7	230.6	307.4
	2 - 4	1.12	-	17.6	35.3	53.00	70.50
	4 - 8	1.00	-	39.7	79.6	119.2	158.9
	8 - 16	0.83	-	45.1	90.1	135.2	180.3
Ignimbrite	0 - 2	2.23	-	104.6	209	313.6	418.0
	2 - 4	1.83	-	28.8	57.6	86.4	115.2
	4 - 8	1.62	-	72.7	128.7	193.1	257.5
	8 - 16	1.54	-	83.6	167.2	250.8	334.4
Crushed Gravel	0 - 2	2.47	463	347.3	231.5	115.8	-
	2 - 4	2.51	158	118.5	79.00	39.5	-
	4 - 8	2.63	418	313.5	209	104.5	-
	8 - 16	2.68	582	436.5	291	145.5	-
Cement (kg/m^3)		3.12	300	300	300	300	300
Water (kg/m^3)			200	200	200	200	200

* A polycarboxylic ether type superplasticizer was used as 4 kg/m^3 in all the mixes.

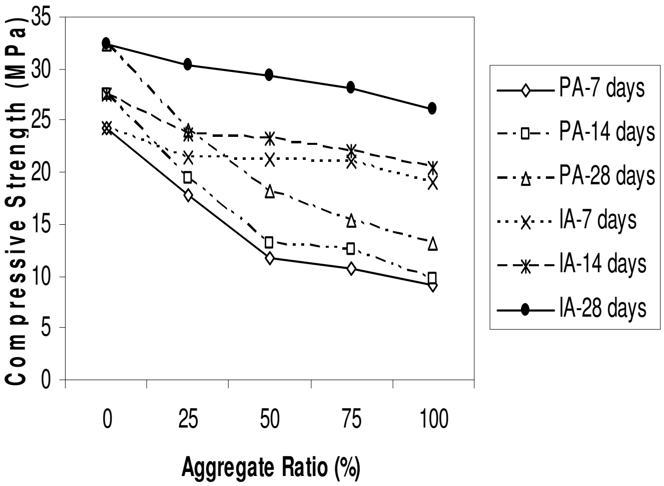

Figure 1. Compressive strength variation of PA, IA, and CGA concretes for different aggregate ratios and ages.

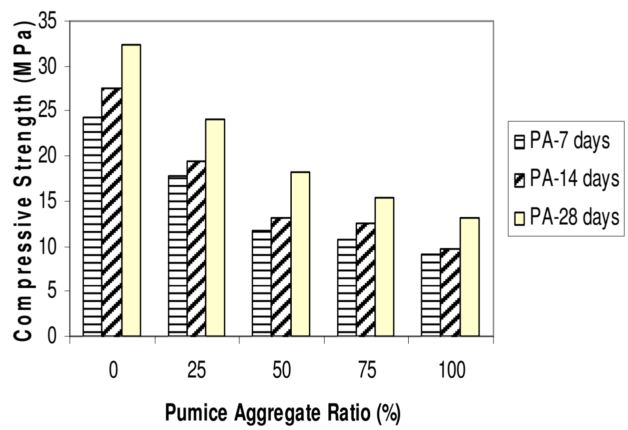

Figure 2. Effect of age, aggregate ratio on the compressive strength of PA concretes.

splitting tensile strength of concrete specimens prepared with the selected low quality and CG aggregates was determined up to 28 days of curing. The influences of aggregate type, ratio and age on the splitting tensile strength of PA, IA and CGA concretes are summarized in Figures 4 - 6. According to control specimens, the splitting tensile strength of PA and IA concretes decreased from 16 - 38 and 8.8 - 16.3% for 7 days, 25.7 - 48 and 15.7 - 22.9 for 14 days and 27.5 - 46.2 and 19.2 - 25.1 for 28 days, respectively. The detailed experimental results are given in Table 4. These results are in good agreement with compressive strength test results and Alonso et al. (2002).

Figure 5 represents the testing age effect on the splitting tensile strength for PA concretes. According to CGA concretes, PA ratio increase, decreased the splitting tensile strength of specimens, but the decrease ratio of splitting tensile strength is decreased for specimens which have PA more than 50%. Figure 6 shows the testing age effect on the splitting tensile strength for IA concretes. According to CGA concretes, IA ratio increase, decreased the splitting tensile strength of specimens. The ratio of this decrease is lower than PA concrete and the decrease ratio of splitting tensile strength is decreased for specimens which have IA more than 50%. The splitting tensile strength and compressive

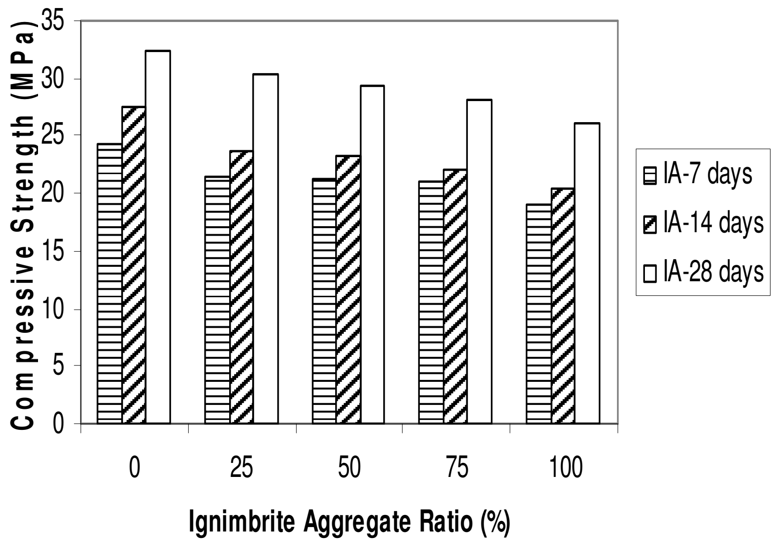

Figure 3. Effect of age, aggregate ratio on the compressive strength of IA concretes.

Table 4. The detailed results of all experiments- a) Compressive strength tests, b) Splitting tensile strength tests, c) Static elastic modulus tests.

Aggregate type	Age (days)	Aggregate ratio (%)				
		0	25	50	75	100
Compressive strength tests						
Pumice	7	24.27	17.87	11.71	10.63	9.10
	14	27.46	19.43	13.20	12.57	9.63
	28	32.45	24.07	18.12	15.39	13.07
Ignimbrite	7	24.27	21.51	21.18	21.00	18.92
	14	27.46	23.57	23.20	22.06	20.53
	28	32.45	30.34	29.25	28.12	26.15
Splitting tensile strength tests						
Pumice	7	2.50	2.10	1.72	1.62	1.53
	14	2.96	2.20	1.87	1.79	1.54
	28	3.38	2.45	2.09	1.92	1.82
Ignimbrite	7	2.51	2.40	2.38	2.33	2.10
	14	2.93	2.59	2.47	2.36	2.26
	28	3.38	2.73	2.66	2.60	2.53
Static elastic modulus tests						
Pumice	7	14.58	11.18	7.76	6.30	5.40
	14	18.21	12.76	9.91	7.58	6.01
	28	19.76	16.01	10.55	10.18	7.69
Ignimbrite	7	14.58	14.51	14.19	13.17	11.33
	14	18.21	17.28	17.17	16.63	16.42
	28	19.76	18.82	18.54	18.03	17.45

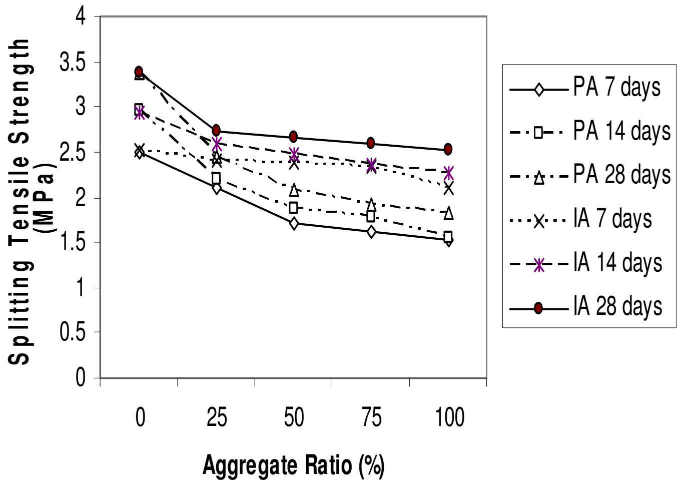

Figure 4. Splitting tensile strength variation of PA, IA, and CGA concretes for different aggregate ratios and ages.

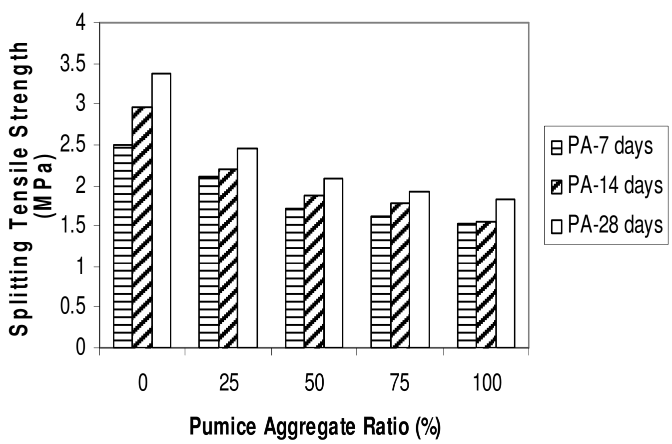

Figure 5. Effect of age, aggregate ratio on the splitting tensile strength of PA concretes.

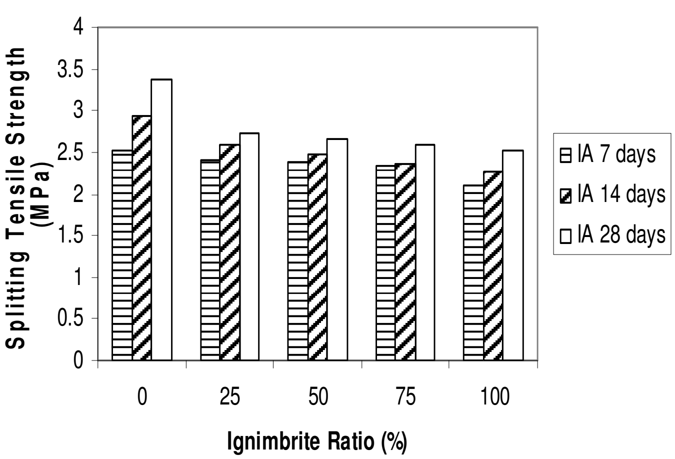

Figure 6. Effect of age, aggregate ratio on the splitting tensile strength of IA concretes.

strength behaves similar but with different decreasing ratios. Many researchers found that the strength deve-opment pattern for splitting tensile strength is similar to that of compressive strength. Mindess and Young (1981) reported that the relationship between tensile and com-ressive strength is complex. According to Neville (1988), splitting tensile strength has a close relationship with compressive strength, but there is no direct propor-ionality. The ratio of the two strengths depends on the general level of concrete strength. In other words, as the compressive strength increases, the tensile strength also increases but at a decreasing rate. However, the splitting tensile strength increases at a much smaller rate when compared to the increase of compressive strength. This implies that the relationship between splitting tensile strength and compressive strength is nonlinear (Zain et al., 2002). These results are in good agreement with Alonso et al. (2002) and Zain et al. (2002).

Static modulus of elasticity

The importance of aggregate quality on elastic properties of concrete was also pointed out by many researchers (Yang, 1997; Almusallam et al., 2004; Alonso et al., 2002). Figure 7 shows the measured values of the static modulus of elasticity of CGA, PA and IA concretes. These data indicate that the type of aggregate has a significant effect on the modulus of concrete elasticity. After 7, 14 and 28 days of curing, the modulus of elasticity of CGA, PA and IA concretes was 14.58, 18.21, 19.76; 5.4 - 11.18, 6.01 - 12.76, 7.69 - 16.01, 11.33 - 14.51, 16.42 - 17.28 and 17.45 - 18.82 GPa, respectively. The detailed experimental results are given in Table 4. As expected, the modulus of elasticity of the CGA concrete was the highest, while that of PA concrete was the lowest. The lower values of the modulus of elasticity of PA concrete may be attributed to the porous nature of these aggregates. Figure 8 shows the testing age effect on the elastic modulus of PA concretes. According to CGA concretes, PA ratio increase, decreased the elastic modulus of specimens. After 7, 14 and 28 days of curing, the modulus of elasticity of PA concretes decreased to about 23.3 - 63, 29.9 - 67 and 19 - 61.1% according to control CGA specimens, respectively. Figure 9 repre-sents the testing age effect on the elastic modulus of IA concretes.

According to CGA concretes, IA ratio increase, decreased the elastic modulus of specimens, but the decreasing ratio of elastic modulus for IA concretes is lower than PA concretes. After 7, 14 and 28 days of curing, the modulus of elasticity of IA concretes decreased to about 23.3 - 63, 29.9 - 67 and 19 - 61.1% according to control CGA specimens, respectively. The elastic modulus of PA concretes is lower with about 23 - 52, 26 - 63 and 15 - 56% than IA concretes after 7, 14, and 28 days of curing. The detailed comparison of each test group may be calculated using Table 4.

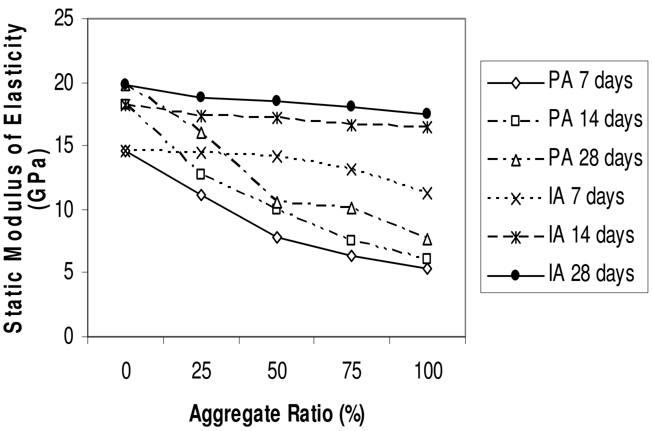

Figure 7. Static modulus of elasticity variation of PA, IA, and CGA concretes for different aggregate ratios and ages.

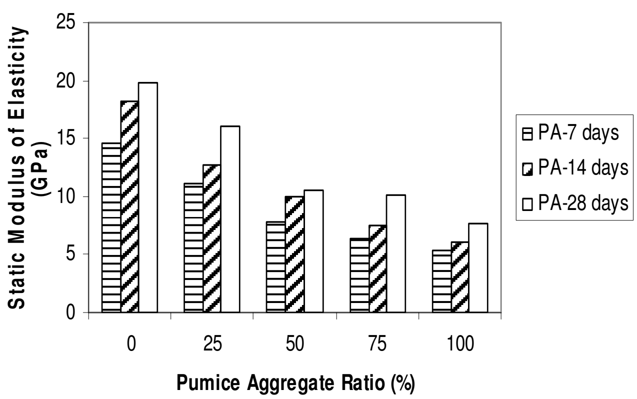

Figure 8. Effect of age, aggregate ratio on the static modulus of elasticity of PA concretes.

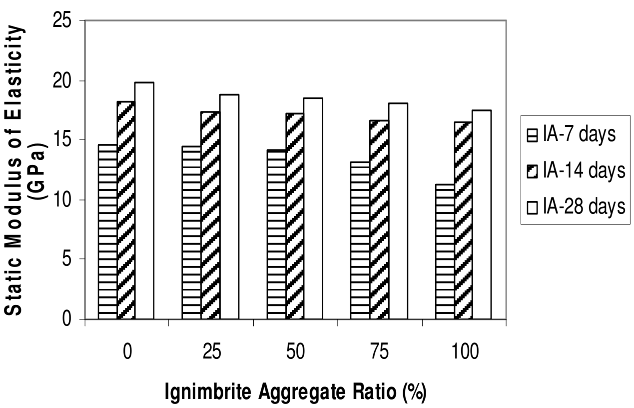

Figure 9. Effect of age, aggregate ratio on the static modulus of elasticity of IA concretes.

Conclusion

The failure in such concretes is often through the aggregates, since the PA and IA are weaker than the CGA. But IA concretes showed more acceptable compressive and splitting tensile strengths than PA concretes. The least strength was noted in the PA concretes.

The type of aggregate also influenced the static modulus of concrete elasticity. Weaker PA tends to produce the least elastic modulus. In such concrete, the bulk of the load is borne by the paste rather than the aggregates alone. The failure in such concretes is often through the aggregates. The lower values of the modulus of elasticity of such concretes may be attributed to the soft nature of used aggregates. Weaker aggregates tend to produce a more ductile concrete than strong aggregates do.

The quality of aggregate has a significant effect on the mechanical properties of concrete. The relatively high compressive strength of ignimbrite aggregates is the most overwhelming property according to its lightness. The compressive and splitting tensile strengths of ignimbrite concretes revealed the confirming values. According to the pumice-like concretes, the ignimbrite concretes had higher strength. So, its usage as a construction material like lightweight concrete, brick or panel is more advantageous in producing cheap and light constructions. Therefore, ignimbrite concretes lighter the building, get less earthquake loads and behave better than gas, pumice or perlite concrete.

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