Comparative Structural Strength Analysis of Pozzolana-Portland Cement Using Ultrasonic Non-destructive Testing Technique

B. J. A. Y. Sogbey[1,2], S. Kwofie[1], E.O. Darko[3], A. A. Adiaottor[1], N. Allotey[2], C. P. K. Dagadu[2]

1. Department of Materials Engineering, Kwame Nkrumah University of Science and Technology, Kumasi Ghana, sobright1knust@yahoo.com
2. Non-destructive Testing Division, National Nuclear Research Institute; Ghana Atomic Energy Commission, P.O. Box LG 80 Legon, Accra, Ghana
3. Department of Nuclear Safety and Security; Graduate School of Nuclear and Allied Sciences, University of Ghana, P.O. Box AE 1 Atomic Energy, Ghana

ABSTRACT

The paper presents comparative results of structural strength analysis of concrete made from a mixture of Pozzolana (Pozzo) and Ordinary Portland Cement (OPC) without reinforcement, at varied ratios of Pozzo/OPC between 0-100 % using ultrasonic non-destructive testing techniques. The Pozzolana content in the mixture was increased in steps of 10 % to obtain an optimum formulation of desired characteristics for nuclear applications. Ultrasonic Pulse Velocity (UPV), one of the most popular non-destructive techniques was used in the assessment of the concrete properties. The study also investigated the relationship between the use of UPV and the Conventional Modulus of Elasticity (CME) to determine concrete uniformity. The UPV tests were carried out at the concrete age of 7, 14, and 28 days. The UPV and the modulus of elasticity of concrete increased with age, but the growth rate varied with mixture proportion. The test results have shown that concrete made from a matrix mixture of 20% Pozzo and 80% OPC has a more improved strength compared to that of the OPC only. Modulus of Elasticity for this improved formulation at ages Seven (7) days, Fourteen (14) days and Twenty-eight (28) days were analyzed.

Keywords: Pozzolana, Non-destructive Testing Technique, Ultrasonic Pulse Velocity, Mechanical Property, Portland Cement, Containment Structure.

1.0 INTRODUCTION

Today it is possible to have an alternative building material to the Ordinary Portland Cement (OPC), which is cheaper in cost. This material (Pozzolana) when used in combination with Portland cement at a particular ratio can exhibit strength comparable to that of pure Portland cement, thereby reducing cost. Pozzolana was named after Pozzuoli (or Pozzoli), a place where variety of volcanic stuff was found near the Bay of Naples in Rome. Portland cement, on the other hand, was named after the Isle of Portland in England when engineer Joseph Aspdin patented the product in 1824 [Kingery *et al.* (1976), Lea, (1970)]. Portland cement is a part of the paste in a concrete mixture that helps hold the aggregates together. A typical concrete mixture will consist of Portland cement, water, aggregates, and possibly admixtures. The ratio of water to cement in a formulation helps determine the strength of the concrete. A concrete with a low water to cement ratio will have a higher strength than a mixture with a higher water to cement ratio [Indian Standards, PPC Specifications, (1993)]. Admixtures may be added to the mix design to accelerate the hydration process and also as retarders that slow the hydration process, air entrainers, plasticizers, super-plasticizers. Pigments may be added to the mix design in order to achieve certain desired results or workability of the concrete. In all cases, curing the concrete in the correct conditions is essential to obtain the desired results.

The OPC is clinker, consisting mostly of calcium silicates, obtained by heating to incipient fusion, a predetermined and homogeneous mixture of materials principally containing lime (CaO) and silica (SiO_2) with a smaller proportion of Alumina (Al_2O_3) and iron oxide (Fe_2O_2), [Indian Standards: PPC Specifications, (1993)]. Pozzolana on the other hand is an essentially siliceous material which while in itself possessing little or no cementitious properties will, in finely divided form and in the presence of water, react with calcium hydroxide at ambient temperature to form compounds possessing cementitious properties. The term includes natural volcanic material having Pozzolanic properties as also other natural and artificial materials, such as diatomaceous earth, calcined clay and fly ash [Indian Standards: PPC Specifications, 1993].

An intimately inter-ground mixture of Portland clinker and Pozzolana with the possible addition of gypsum (natural or chemical) or an intimate and uniform blending of Portland cement and fine Pozzolana [Indian Standards: PPC Specifications, 1993]. An ideal environment for concrete curing is one in which the concrete is kept hydrated until the process of hydration is complete. Good hydration will decrease the permeability but ultimately increase the strength of the concrete.

The objective of this paper is to comparatively investigate the structural strength of concrete made from OPC and Pozzolana cement at varied ratios, using ultrasonic techniques. Structural strength determined using compressive methods proved that 20% Pozzolana in Portland cement paste yielded higher strength than that of the control (OPC). [Sogbey, et al, 2012].

2.0 Ultrasonic Testing Model for Concrete Structural Analysis

Ultrasonic methods have been used for assessing comparative strength of concrete, detecting flaws such as voids or cracks, and estimating member thickness [Krautkramer, (1969)]. Ultrasonic techniques involve the propagation and detection of mechanical vibrations that have interacted in some way with the structure under test. When the surface of a semi-infinite solid is excited by a time varying mechanical force, energy is radiated from the source as three distinct types of elastic wave propagation. The fastest of these waves has particle displacements in the direction of travel of the disturbance and is called the longitudinal, compression or P-wave. The Compression Wave Velocity V_p is a function of the dynamic Young's modulus E, the Poisson's ratio υ, and the mass density ρ, and is given by

$$\mathbf{V_p} = \sqrt{\frac{\mathbf{E}(\mathbf{1 - v})}{\rho(1+\mathbf{v})(1-2\mathbf{v})}} \qquad \mathbf{(1)}$$

or the Longitudinal Pulse Velocity (V_p), is given by $\mathbf{V_p} = \frac{\mathbf{L}}{\mathbf{T}}$ (km/s or m/s)

Where, V_p is the longitudinal pulse velocity, L is the path length, T is the time taken by the pulse to traverse that length.

The second fastest is the shear, transverse or S-wave, which has particle displacements perpendicular to the propagation direction. The shear wave velocity V_s is a function of the dynamic shear modulus G and ρ, expressed by the relation

$$\mathbf{V_S} = \sqrt{\frac{\mathbf{G}}{\boldsymbol{\rho}}} \qquad (2)$$

Young's and the shear moduli are related by **E= 2G(1+v)** (3)

Compression and shear wave velocities are theoretically interrelated by Poisson's ratio υ, which can be expressed as:

$$\upsilon = \frac{0.5 - \left(\frac{V_S}{V_P}\right)^2}{1 - \left(\frac{V_S}{V_P}\right)^2} \qquad (4)$$

The compression and shear waves propagate throughout the material in all directions. The third type of wave-motion produced travels along the surface and has elliptical particle motion, where the component of displacement normal to the surface is greater than the component in the direction of wave propagation. The velocity, V_R, of this surface wave, known as the Rayleigh wave, in simplified form is given by

$$V_R = AV_S \qquad (5)$$

where A is a function of υ and V_S. The ratio of V_R/V_S increases as Poisson's ratio increases. For values of υ from zero to 0.5, the ratio of V_R/V_S changes from approximately 0.87 to 0.96. Ultrasonic inspection of concrete is basically the evaluation of one or more of these wave velocities. Since wave velocity is a direct indication of stiffness of the material, a higher wave velocity is associated with higher stiffness. When an ultrasonic wave is incident on a plane boundary between two media, some of the ultrasonic energy is transmitted through the boundary and some is reflected. The percentages of energy transmitted and reflected depend on the specific acoustic impedance, Z,

$$Z=\rho V \qquad (6)$$

where ρ is the density of the material and V is the velocity of the wave. For two materials of different acoustic impedances Z_1 and Z_2, the percentage energy transmitted, E_T, is given by (Halmshaw, 1987).

$$E_T = \frac{4Z_1Z_2}{(Z_1Z_2)^2} x100 \qquad (7)$$

and the percentage of reflected energy, E_R, is given by:

$$E_R = \left(\frac{Z_1 - Z_2}{Z_1 + Z_2}\right)^2 x100 \qquad (8)$$

The equations are valid for both compression and transverse waves, but as transverse wave cannot be sustained in a liquid, a transverse wave at normal incidence is always completely reflected at a solid/liquid or solid/gas interface. The resolution of an interrogating signal is indirectly proportional to signal wavelength λ, given by the relationship:

$$c = \lambda f \qquad (9)$$

where c is the phase velocity and f is the frequency of excitation. Additionally, an electro-acoustic transducer has directional properties, where the main energy falls to zero at an angle of divergence θ, given approximately by

$$\sin\theta = \frac{1.22\lambda}{D} \qquad (10)$$

where D is the diameter of the transducer (Krautkramer, 1969). Thus high frequencies in the MHz range are preferred for ultrasonic inspection. In practice an upper limit is imposed on the frequency by very high attenuation of vibrations whose wavelengths are comparable with the grain size of the material to be inspected. For fine grained materials such as steel or aluminium, frequencies of tens of MHz will propagate without undue attenuation, and thus it is possible to produce a pulse in which most of the energy is contained within a beam of about 5° for a 16 mm 5MHz transducer. In structural concrete however, the coarsest aggregate is of the order of 20 mm, which imposes a practical upper limit of several hundred kHz. Frequencies of the order of 50 kHz to 100 kHz are popular for long range inspection of concrete, (10 m for 54 kHz to 3 m for 82 kHz), however these frequencies imply wavelengths around 50 mm, which for a standard 50 mm diameter transducer, offers no directional properties at all and low resolution [J.H. Bungey and S.G. Millard,**(year)].** Figure 1 illustrates measurement of ultrasonic pulse velocity (UPV).

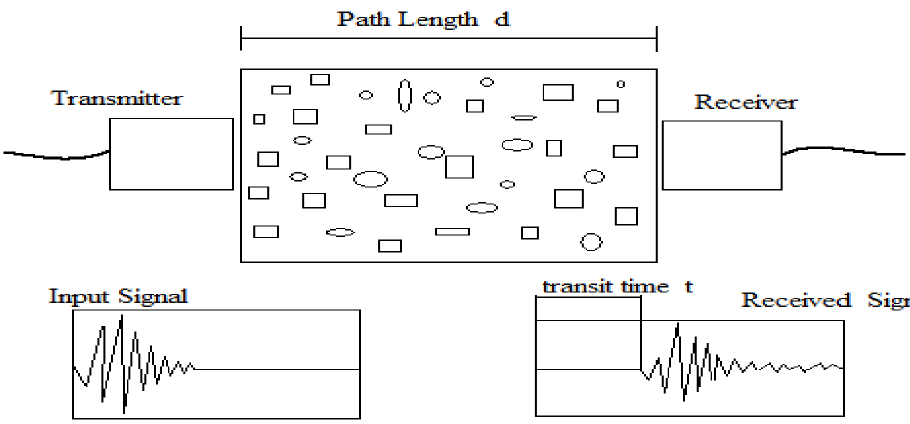

Figure 1: Ultrasonic pulse velocity testing

2.1 Determination of pulse velocity

A pulse of longitudinal vibrations was produced by an electro-acoustical transducer, which was held in contact with one surface of the concrete under test. When the pulse generated was transmitted into the concrete from the transducer using a liquid coupling material such as grease or cellulose paste, there were multiple reflections at the boundaries of the different material phases within the concrete. A complex system of stress waves developed, which included both longitudinal and shear waves, and propagated through the concrete. The first waves to reach the receiving transducer were the longitudinal waves, which were converted into an electrical signal by a second transducer. Electronic timing circuits enabled the transit time T of the pulse to be measured.

3.0 Materials and Methods

This section presents the materials used and methodology employed in sample (concrete) preparation and testing. Ultrasonic test was carried out on the Pozzolana-OPC concrete mixture. The Pozzolana was obtained from BRRI-CSIR, Kumasi.

ASTM type-1 OPC used as reference was taken from the cement factory (GHACEM). The chemical composition of Pozzolana and OPC used in the present work are as shown in Table 1. Crushed gravel with a maximum nominal size of 10 mm was used as coarse aggregate and natural sand conforming to Zone II with a fineness of 2.52 mm was used as fine aggregate.

Table 1: Chemical Composition of Portland and Pozzolana Cement (%wt)

	Chemical Composition (% wt)	
Compound	**Pozzolana**	**Portland**
SiO	46.25	27.43
Al_2O_3	17.34	5.4
Fe_2O_3	10.26	3.48
CaO	10.18	53.71
MgO	2.9	1.41
K_2O	1.64	0.92
Na_2O	3.64	0.16
SO_3	0.8	2.59
Cl^-	0.01	0.004

Source: [SBEIDCO, (2009)]

3.1 Sample Moulding and Testing

The mix of cement, sand and stone used for all concrete cubes and cylinders cast in this work were in the ratio 1:2:4 with the OPC partially replaced by Pozzolana in varied percentages of its weight from 0 % to 100 % in stepwise increments of 10 %. The pastes were elaborated in cubic moulds (wooden) of 15 x 15 x 15 cm^3 and cylindrical moulds (plastic) of diameter 10 cm and 50 cm long. Equipment used were compression testing machine, flexural test machine, electronic vibrator, shovels and other mixing apparatus all from the Ghana Standards Board and the ultrasonic test machine at the Ghana Atomic Energy Commission.

Plastic sheets were used to cover the specimens to prevent water from evaporating. After 24 hours, the specimens were striped from their respective moulds. The strength

tests were carried out at 7, 14, and 28 days and the average test results of three specimens for each percentage of Pozzolana introduced for each test were recorded. In the case of mixes prepared at water binder ratio of 0.5, the compressive strength studies were started at the end of 2 days instead of 7 days. The test procedure followed during the test was in conformity with [BS (1881): Part 116 (1983)].
To validate the results, compressive tests were carried out using compression testing machine in the range 0-2000 kN crushing force and ultrasonic test machine of frequency 10 MHz. Flexural test was also conducted only on 28 days' curing of cylindrical specimen with water to cement ratio of 0.5.
Table 2 and 3 shows the percentage compositions and weights of OPC and Pozzolana in the nine (9) test sample matrix.

Table 2: Portland/Pozzolana Mixture (Ratios)

Sample	S0	S1	S2	S3	S4	S5	S6	S7	S8	S9
Portland	control	90%	80%	70%	60%	50%	40%	30%	20%	0%
Pozzolana	0%	10%	20%	30%	40%	50%	60%	70%	80%	control

Table 3: Percentage Composition Of Materials in the Mixture Matrix

Sample	Weight of OPC, kg	Weight of Sand, kg	Weight of Stone, kg	Weight of Pozzolana, kg	Water, ml
S0-Control	4.0	8	16	0.0	2000
S1- 10% Pozzo	3.6	8	16	0.4	2000
S2- 20% Pozzo	3.2	8	16	0.8	2000
S3-30% Pozzo	2.8	8	16	1.2	2000
S4- 40% Pozzo	2.4	8	16	1.6	2000
S5- 50% Pozzo	2.0	8	16	2.0	2000
S6- 60% Pozzo	1.6	8	16	2.4	2000
S7-70% Pozzo	1.2	8	16	2.8	2000
S8- 80% Pozzo	0.8	8	16	3.2	2000
S9- Control	0	8	16	4.0	2000

4.0 RESULTS AND DISCUSSION

4.1 Mechanical behavior

Figures 2, 3 and 4 show plots of Elastic Modulus against the percentage weight of pozzolana in the mixture matrix of concrete.

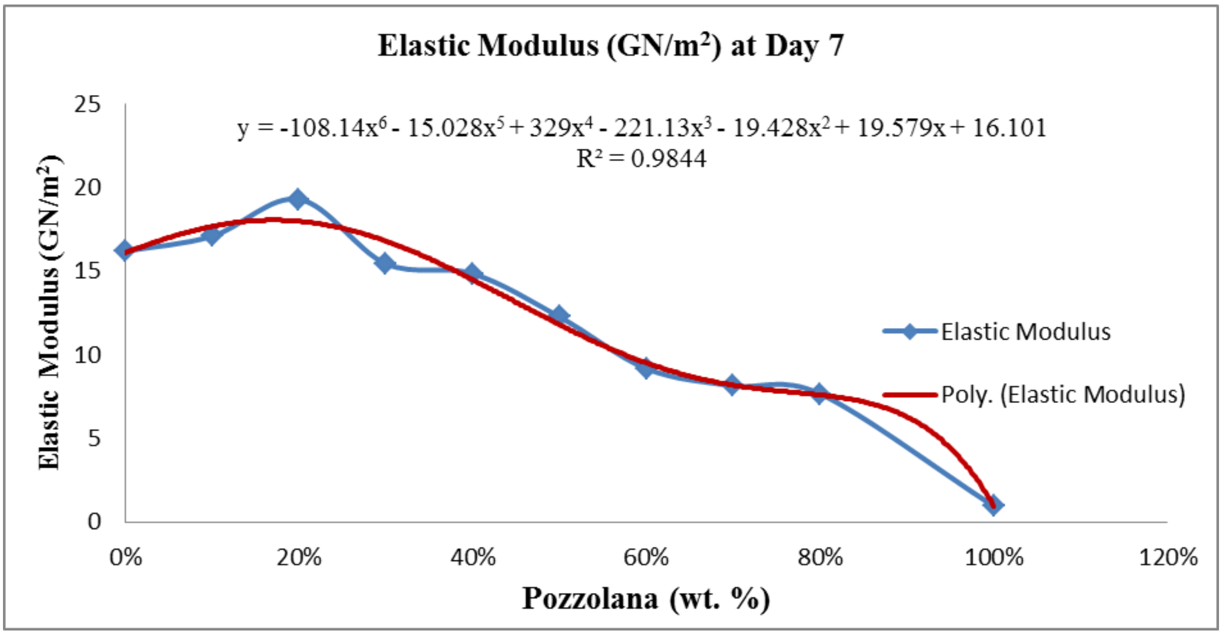

Figure 2: Graph of Avg. Elastic Modulus versus Pozzolana (wt. %) at Day 7

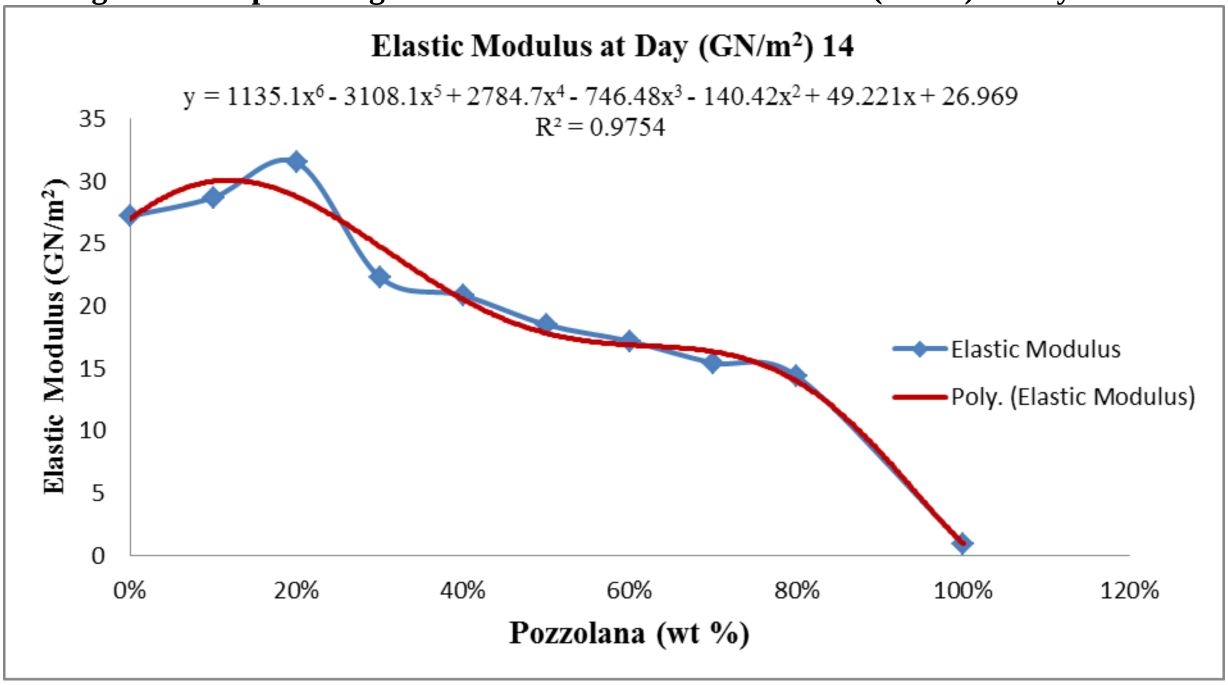

Figure 3: Graph of Avg. Elastic Modulus versus Pozzolana (wt. %) at Day 14

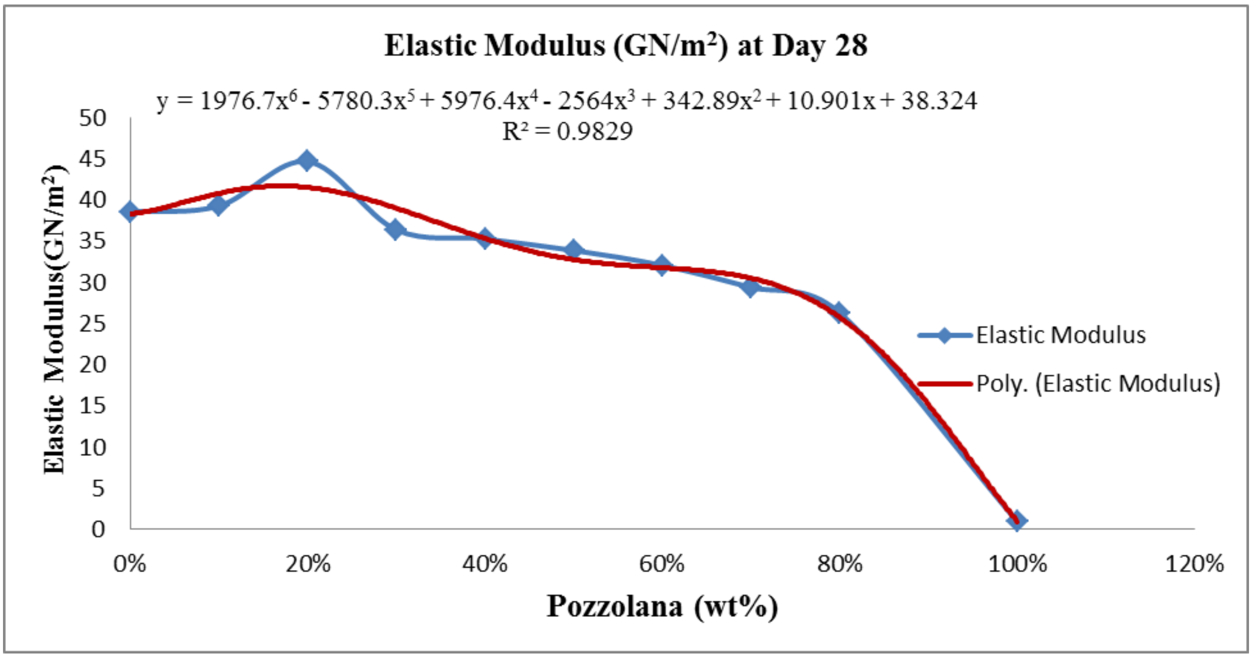

Figure 4: Graph of Avg. Elastic Modulus versus Pozzolana (wt. %) at Day 28

It is evident from figure 2, 3 and 4 that, when no Pozzolana was introduced in the concrete formulation (Pure Ordinary Portland Cement), the values of elastic modulus were 16.2, 27.2 and 38.6 GN/m^2 respectively. These values however increased as the content of Pozzolana increased in the formulation until the graphs peaked at the point when 20 % Pozzolana was introduced. The graphs then drops with further increase in the Pozzolana content till it attained an almost zero value at 100% Pozzolana content. This characteristic strength realized at the addition of 20 % Pozzolana was attributed to the effective chemical reaction between the components (especially CaO and SiO) of Pozzolana and the ordinary Portland cement in the mixture matrix.

The cost of Pozzolana presently is about 33.3% that of Ordinary Portland Cement. However this alone could not be used to produce concrete to meet any desired strength. Although relatively, a desired strength could be obtained by using only Ordinary Portland Cement, it is not economical and hence not affordable. A higher strength of concrete, even better than that obtained when only ordinary Portland cement is used is economically produced when for every 4 parts of ordinary Portland cement, 1part of pozzolana is added.
The concrete produced is excellent when its Ultrasonic Pulse Velocity is above 4500. Table 4 shows the quality of concrete as a function of the UPV.

Table 4: Quality of concrete as a function of the ultrasonic pulse velocity (UPV)

Vp (m/s)	**Concrete Quality**
Above 4500	Excellent
3500 - 4500	Good
3000 - 3500	Doubtful
2000 -3500	Poor
Below 2000	Very Poor

Source: [Qasrawi, (2000)].

As shown in figure 7, 8, and 9, the Ultrasonic Pulse Velocities obtained for the present analysis at 20% pozzolana content increased from 3350 on the 7th day through 4400 on the 14th day to 4500 on the 28th day of ageing of the concrete. The quality of the concrete produced will therefore be excellent after 28 days of ageing.

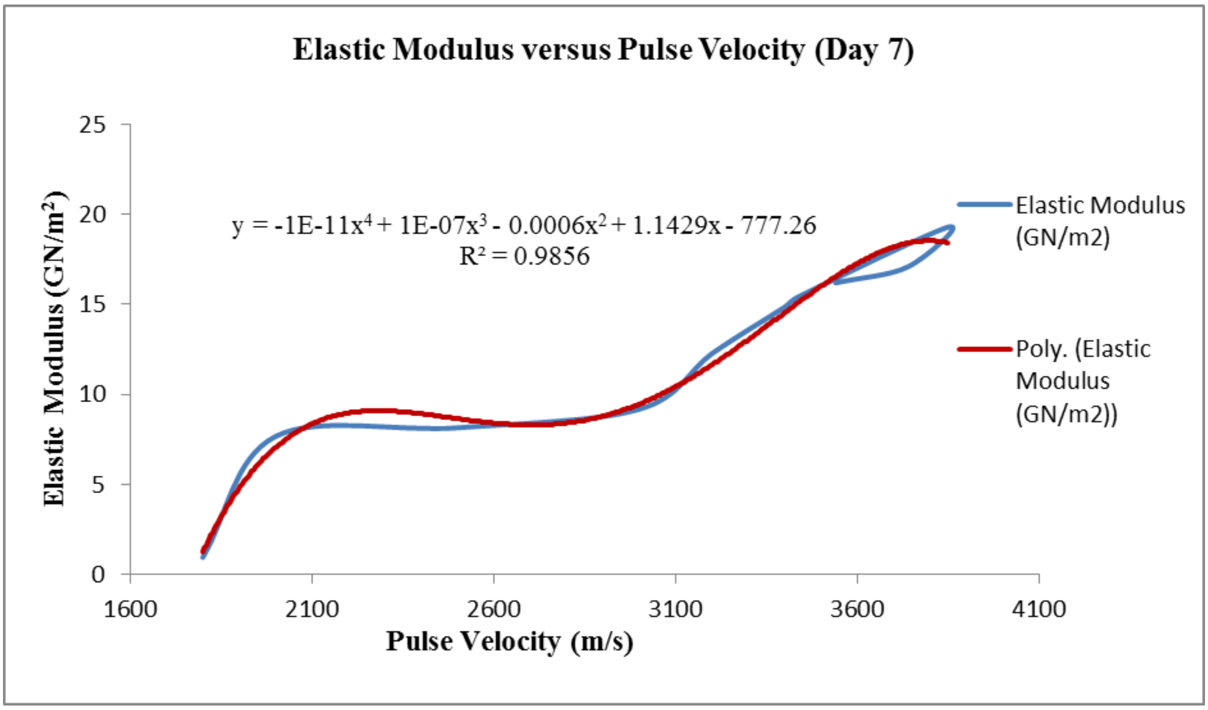

Figure 7: Graph of Elastic Modulus versus Pulse Velocity for 7-day test

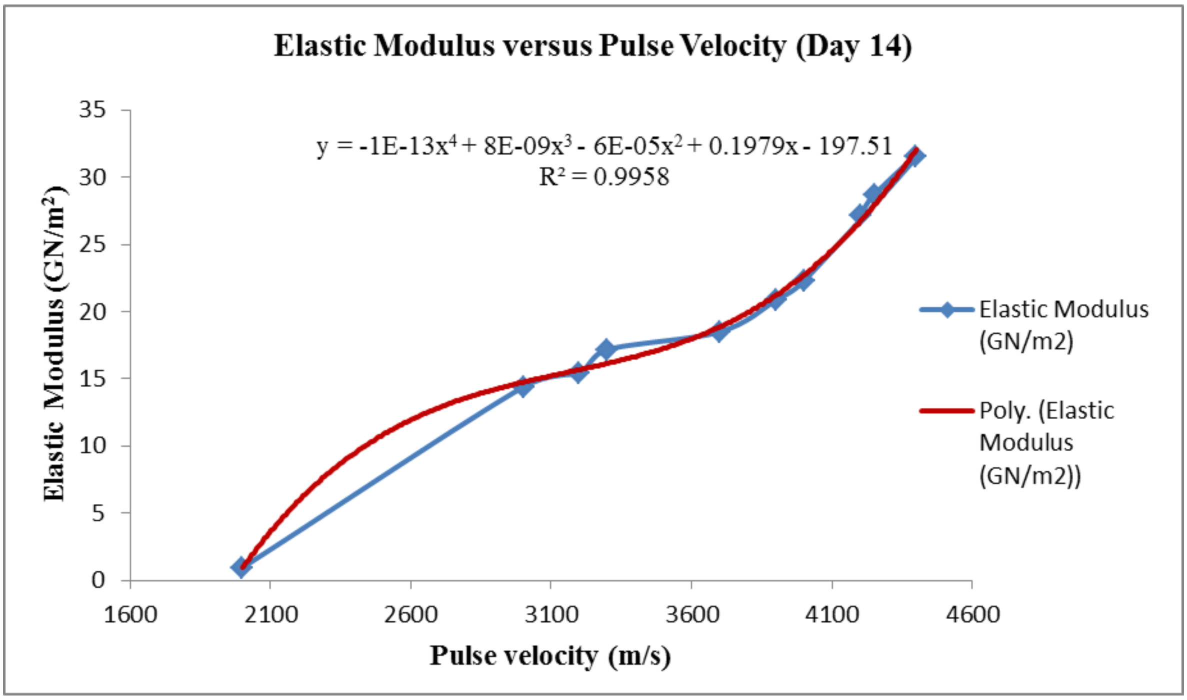

Figure 8: Graph of Elastic Modulus versus Pulse Velocity for 14-day test

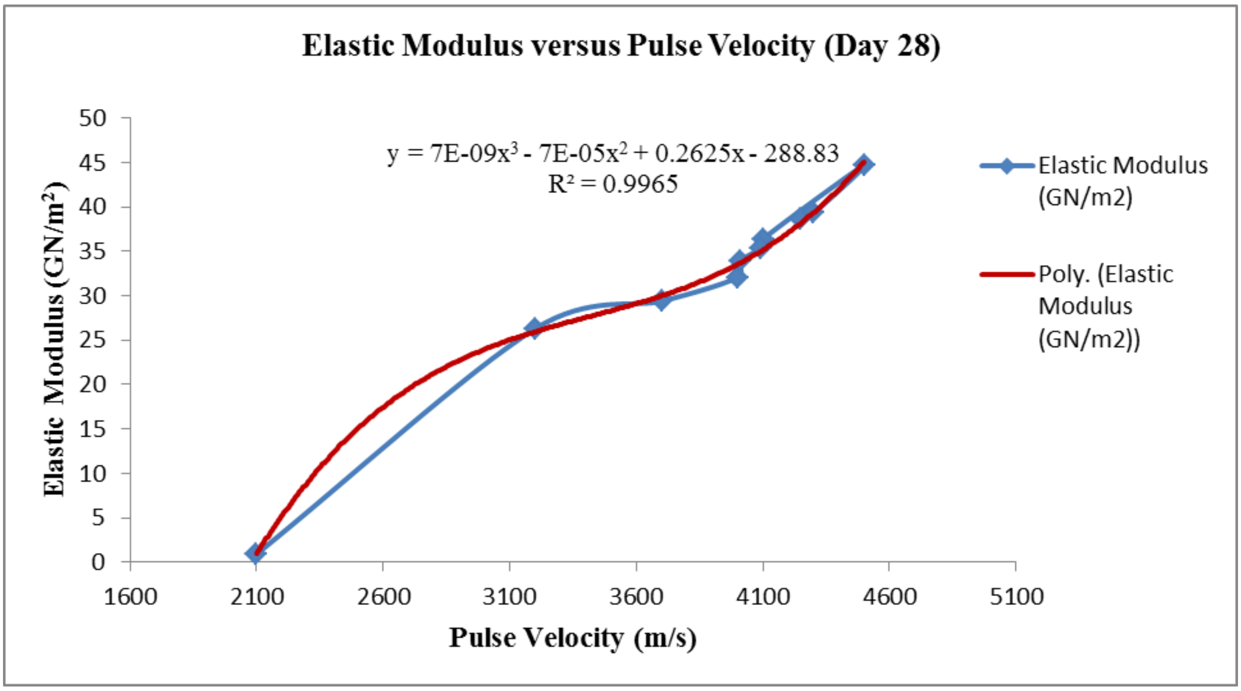

Figure 9: Graph of Elastic Modulus versus. Pulse Velocity for 28-day test

5.0 CONCLUSION

Ultrasonic Test was performed to determine the Pulse Velocity and the Modulus of Elasticity of concrete produced from Pozzolana and ordinary Portland cement at increasing percentage of Pozzolana in the mixture matrix. The pulse velocity is a measure of concrete quality whiles the modulus of elasticity is a function of concrete strength. From the experiments it has been realized that, 100% Pozzolana has little or no strength and as such cannot be used all alone for the purpose of loads of any kind, unless used in combination with ordinary Portland cement (OPC). An improved characteristic strength of concrete at considerably lower cost was obtained when 20% of Pozzolana was mixed with 80% of Ordinary Portland cement. The value of the modulus of elasticity which is higher than that obtained when only the ordinary Portland cement was used increased with ageing. The quality of the concrete tested also increased from a doubtful stage to an excellent concrete after 28 days of curing. It has therefore been confirmed in this work that, it is not only very economical to produce concrete from a blend of Pozzolana and Ordinary Portland cement in the ratio of 1:4 but also, an improved strength of concrete suitable for application for reinforced construction works is obtained.

6.0 ACKNOWLEDGMENTS

I acknowledge the contribution from Ghana Atomic Energy Commission (GAEC), Mr Nikolas Sosu, Head, Engineering Section, Ghana Standards Board (GSB), Mr. William Nimako, Head, Civil Engineering Laboratory, GSB, Messrs Isaac Lawson, Vincent Agbodemegbe and Said Ibrahim Said all of Department of Nuclear Engineering, University of Ghana: Francis Mudy and Mawuli Tsaku of Civil Engineering Laboratory, GSB. W.O Armah: Dept. of Physics, University of Ghana, Legon and Appropriate Technology Support Division; Science and Technology Advocacy Renaissance Foundation for Africa (STARFA), Ghana.

7.0 REFERENCES

1. ACI (1996). "Specifications for structural concrete for buildings" *Amercian Concrete Institute*.
2. BLACKLER, M.J., R.S. COOKE, Besses O'Th' Barn Bridge (1995). "Inspection and testing of a segmental post-tensioned concrete bridge" *Proc. Inst. Civ. Engrs. Structs. & Bldgs*. pp 110.
3. BRITISH STANDARDS INSTITUTION (1986). "Non-destructive methods of test for concrete electromagnetic cover measuring devices" *London, British Standard* pp 4408.
4. BS 1881: Part 201 (1986). "Guide to the use of non-destructive methods of test for hardened concrete" *London, British Standards Institution*.
5. BS 1881: Part 203 (1986). "Recommendations for measurement of velocity of ultrasonic pulses in concrete" *London, British Standards Institution.*
6. BS 1881: Part116 (1983). "Method for determination of compressive strength of concrete cubes" *London, British Standards Institution*.
7. Bungey J.H. and S.G. Millard (1996). "Testing of concrete structures" *London, Blackie Academic & Professional*.
8. Qasrawi H.Y. (2000). "Concrete strength by combined non-destructive methods simply and reliably predicted".
9. SBEIDCO (2009). "1st International Conference on Sustainable Built Environment Infrastructures in Developing Countries" *Algeria - October 12-14, ENSET Oran*.
10. Sogbey B. J. A. Y, Danso K. A., Fletcher J. J. , Lawson I. and Ibrahim S. I. (2012) 'Concrete Formula, Using Pozzolana/Portlant Cement for Superstructures in Nuclear Engineering' Journal of the Ghana Institution of Engineers, Vol. 9 pp 15 – 22.

Appendix A

Table 5: Results of Seventh (7th) Day Ultrasonic test

Pozzolana wt. %	Avg. Velocity (m/s)	Avg. Plastic Modulus (GN/m2)
S0 (Control) Portland	3540	16.2
S1 (10% Pozzolana)	3740	17.1
S2 (20% Pozzolana)	3850	19.3
S3 (30% Pozzolana)	3440	15.45
S4 (40% Pozzolana)	3400	14.85
S5 (50% Pozzolana)	3200	12.27
S6 (60% Pozzolana)	3000	9.18
S7 (70% Pozzolana)	2500	8.15
S8 (80% Pozzolana)	2000	7.67
S9 (Control) Pozzolana	1800	0.95

Table 6: Results of Fourteenth (14th) Day Ultrasonic test

Pozzolana wt. %	Avg. Velocity (m/s)	Avg. Plastic Modulus (GN/m2)
S0 (Control) Portland	4200	27.2
S1 (10% Pozzolana)	4250	28.7
S2 (20% Pozzolana)	4400	31.5
S3 (30% Pozzolana)	4000	22.3
S4 (40% Pozzolana)	3900	20.85
S5 (50% Pozzolana)	3700	18.5
S6 (60% Pozzolana)	3300	17.18
S7 (70% Pozzolana)	3200	15.44
S8 (80% Pozzolana)	3000	14.4
S9 (Control) Pozzolana	2000	0.95

Table 7: Results of Twenty Eighth (28th) Day Ultrasonic test

Pozzolana wt. %	Avg. Velocity (m/s)	Avg. Plastic Modulus (GN/m2)
S0 (Control) Portland	4250	38.6
S1 (10% Pozzolana)	4300	39.3
S2 (20% Pozzolana)	4500	44.7
S3 (30% Pozzolana)	4100	36.4
S4 (40% Pozzolana)	4090	35.3
S5 (50% Pozzolana)	4010	33.9
S6 (60% Pozzolana)	4000	32.08
S7 (70% Pozzolana)	3700	29.4
S8 (80% Pozzolana)	3200	26.3
S9 (Control) Pozzolana	2100	0.95