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Effects of Portland cement addition on Young's modulus of geopolymer concrete cured at ambient conditions

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Abstract. This paper presents the results of Young's modulus and Poisson's ratio tests conducted on samples made of low-calcium fly ash-based geopolymer concrete samples and on samples with a 10% addition of Portland cement, cured at ambient conditions. Furthermore, the measurement system, as well as sampling and sample preparation methodology, are discussed. Strain was tested concurrently using resistive strain gauges and extensometer on cylinder-shaped samples with a diameter of 150 mm and height of 300 mm.
Keywords: engineering, construction materials, geopolymer concrete, Young's modulus, Poisson's ratio, alkali-activated concrete
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1. Introduction

The first geopolymer material was patented in 1979 by J. Davidovits [1]. Geopolymers are synthetic inorganic aluminosilicate polymers. They can be produced by mixing pozzolan materials with activators consisting of solutions of silicates and strong alkali. Geopolymer applications are extensive. They can be used to manufacture ceramic elements, construction materials, and as injections for repairing

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existing structures. Furthermore, according to Davidovits, geopolymers were used to produce construction elements for the pyramids in Egypt [2]. One direction of geopolymer use in engineering that is studied today is geopolymer concrete production. It is manufactured using waste from industrial processes, which is of great value for combating environmental pollution, currently a major issue for the developing world. The industrial waste of the greatest potential in engineering, providing the best properties of concrete, is fly ash [3-11]. In Poland, due to the significant share of energy produced from coal, large amounts of various types of ash are generated. Geopolymer concrete production is therefore an opportunity to utilise significant amounts of coal combustion waste.

The most comprehensive studies on Young's modulus of geopolymer concrete are presented for example in papers [9, 12-14]. Some of these studies [9, 13, 14] also specify Poisson's ratio of geopolymer concrete. The small number of studies conducted on this subject is notable. All these studies concern materials with compositions differing in aggregate types, additives, activator types and their ratios to fillers. Furthermore, all samples made within those studies were heat-cured during the initial stage of polymerisation.

The purpose of the experiments described in this paper was to determine Young's modulus and Poisson's ratio of low-lime fly ash-based geopolymer concrete that was not subjected to additional curing at elevated temperatures during the maturation.

Conventional fly ash (FA) used for investigations was provided by PGNiC Termika S.A. The ash has been obtained from the Żerań Coal-fuelled Power Station in Warsaw. It was subjected to X-ray fluorescence spectroscopy (XFS analysis) at the Central Chemical Laboratory of the Polish Geological Institute. It was stated on the basis of the carried out analysis that total content of silicon oxide, aluminium oxide, iron oxide is 83.32% and calcium oxide is 3.55%. These parameters in connection with loss on ignition (LOI) of about 5.12% allow to qualify this ash to the class F, according to [15], and as siliceous fly ash (V) according to [16].

For concrete, the magnitude of strain is somewhat dependent on the stress rate. Extending the loading time results in an increased strain on the material. Concrete strain increase is also affected by creep. In order to eliminate the effect of this factor on the results, it was decided that the reliable concrete strain modulus is secant modulus determined through momentary loading and unloading. Furthermore, considering that strain modulus decreases with increasing reference stress at which it is determined, the literature and standards assume different values of this stress in relation to concrete strength. According to the standard BS 1881-121 point 5.2 [17], it is $f_c/3$ (33%) in strength. This value is also consistent with the provision in EN 12390-13 point 7.3 [18]. However, according to ASTM C 469-02 point 6.4 [19], reference stress should be 40% of concrete strength. Another important issue addressed in all of the above-mentioned standards is the requirement to apply a preliminary load to each newly tested sample.

2. Object of study

The object of the study was geopolymer concrete based on low-calcium fly ash. A mixture of aqueous sodium solution ($NaOH_{sol}$) with molarity of 10 with sodium silicate in the form of sodium water glass (SS_{sol}), commercial designation R-145, was used as an activator.

The tests were conducted on geopolymer concrete samples prepared using two mixture formulas, show in Table 1. In the first sample group — FA100, only fly ash was used as filler. The other group — OPC10, included a modification that involved replacing 10% of fly ash with quick-binding Portland cement CEM I 42.5R. No other additives were used in either case. The formulas of both mixtures are shown in Table 1.

TABLE 1

Formulas of mixtures FA100 and OPC10

Concrete mixture formulas		
Component	FA100 [kg/m^3]	OPC10 [kg/m^3]
Aggregate weight	1452	*1452*
coarse aggregate mass	726	726
fine aggregate mass	726	726
binder mass	968	*968*
ash mass	645	580
cement mass	-	65
activator mass	322	322

Two types of aggregate were used to prepare the concrete. One was sand with a grain size 0 – 2 mm, the other — basalt aggregate with a grain size 2 – 8 mm. Their ratios were selected to achieve the greatest waterproofness. The SS_{sol} to $NaOH_{sol}$ ratio was chosen at 2.5, while the ratio of activator to fly ash at 0.5. The activator was prepared at least one day before use.

During sample preparation, aggregate was poured into the laboratory mixer, and then fly ash and cement were added. The dry components were mixed for 3 min. After this time, a measured amount of activator was added. The blend was then mixed for 10 minutes. After this time, the blend was placed in ø150 × 300 mm steel moulds.

Geopolymer samples prepared in this manner were aged under laboratory conditions and were not subjected to additional curing under elevated temperature or humidity. The samples were removed from the moulds after 3 days. The tests were conducted after 28 days from placing the concrete blend in the moulds.

Before the main tests were performed, the strength of the cylindrical samples was tested to determine the load range for further experiments. Compressive strength was 25.8 MPa (destructive force 455.5 kN).

3. Measurement procedure

The samples were loaded using a hydraulic strength test machine ZD40 with an operating range up to 400 kN. During testing, the loading force was recorded using the integrated measurement module. Before the tests proper, the accuracy of recording was tested. To this end, a comparison measurement was performed using the PCB 200C50 SN 3545 force sensor. Voltage from the sensor was transmitted to the Agilent U2351A analog-digital converter and recorded on a PC. The result confirmed that the strength test machine control module recorded force values correctly.

Longitudinal strain was measured using two methods. Local strain of each sample was recorded using two resistive strain gauges attached to opposite sides of the sample. Gauges with a measurement base of 50 mm, resistance 120 Ω and gauge factor 2.09 were used. Lateral strain was measured in an identical manner. KWS106D strain amplifier with double signal amplification was used for the tests. Additionally, longitudinal strain was recorded using an Epsilon 3542RA2 axial extensometer. The signal was amplified 10-fold. Before measurements were started, the extensometer was calibrated using an Epsilon 3590 device. The total measurement error for the system branch with the strain gauges was $|\varepsilon_{u2}| \leq 0{,}11\%$, while for the extensometer branch it was $|\varepsilon_{u3}| \leq 0{,}21\%$.

Signals from the amplifiers were directed to an Agilent U2351A A/D converter with a resolution of 16 bit. Data received from the recorders were synchronised relative to characteristic points on the resulting charts. To this end, identical sampling was set in all recorders. A diagram of the measurement system is shown in figure no. 1.

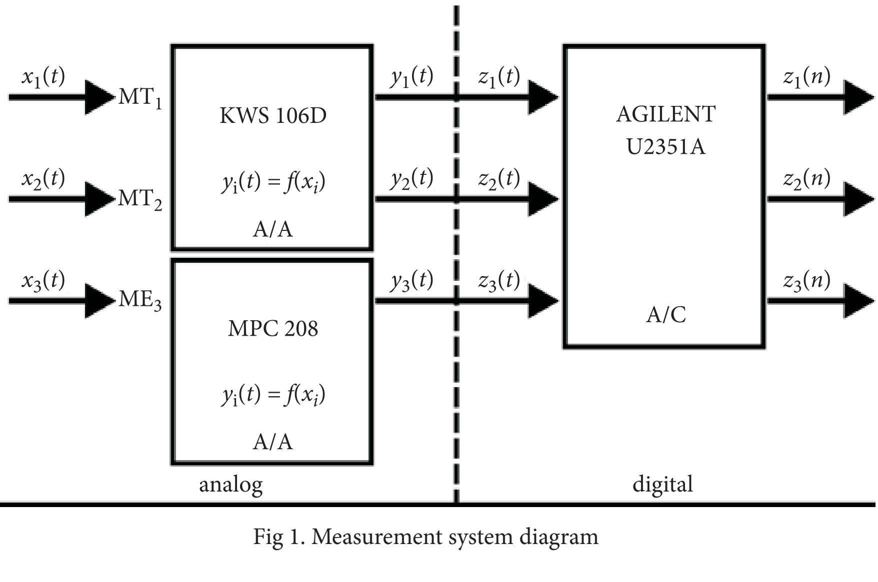

Fig 1. Measurement system diagram

The diagram shows: $x_1(t)$, $y_1(t)$, $z_1(t)$ i $z_1(n)$ — longitudinal strain measurement, $x_2(t)$, $y_2(t)$, $z_2(t)$ i $z_2(n)$ — lateral strain measurement, $x_3(t)$, $y_3(t)$, $z_3(t)$ i $z_3(n)$ — longitudinal strain measurement from the extensometer, MT_i — tensometric bridge and ME_i — extensometer bridge.

Full Wheatstone tensometric bridges were used in every measurement path, together with two active strain gauges attached to the cylinders to be loaded, and two compensation strain gauges attached to non-loaded elements made of the same materials as the test samples.

The maximum value of the main load of samples was P_g = 180 kN and was maintained for 20 seconds. The minimum value of the main load was chosen as P_d = 20 kN. The main load increase rate was 0.2 MPa/s. The maximum main load value corresponded to 40% of destructive load (455.5 kN) what complies with ASTM C 469-02 standard. Before the main loading cycle, two preliminary loading cycles were performed with a force of 40 kN maintained for 20 seconds.

Young's modulus was calculated as a ratio of the difference between top and bottom stress to the difference of corresponding strains:

$$E_c = \frac{\sigma_g - \sigma_d}{\varepsilon_g - \varepsilon_d}, \tag{1}$$

where: σ_g — top stress generated by force P_g,
σ_d — bottom stress generated by force P_d,
ε_g — strain corresponding to σ_g,
ε_d — strain corresponding to σ_d.

Poisson's ratio was calculated as a ratio of lateral strain $\varepsilon_{g\perp}$ to longitudinal strain $\varepsilon_{g||}$ of the sample, for strains occurring under top stress:

$$\nu = \frac{\varepsilon_{g\perp}}{\varepsilon_{g||}} \tag{2}$$

4. Test results

Four tests with vertical strain recording using extensometer and two tests each with correct recording of vertical and horizontal strain using strain gauges were conducted on the FA100 samples. For the OPC10 samples, five tests with vertical strain recording using extensometer, two tests with recording of vertical strain and three with recording of horizontal strain using strain gauges were conducted. Young's modulus and Poisson's ratio values calculated for individual samples are shown in Table 2.

Table 2

Young's modulus and Poisson's ratio values

Young's modulus and Poisson's ratio			
sample	strain gauge Young's modulus E_c [GPa]	extensometer Young's modulus E_c [GPa]	Poisson's ratio ν
FA100 — 1	11.52	10.0	—
FA100 — 2	10.67	9.9	—
FA100 — 3	—	12.4	0.13
FA100 — 4	—	12.6	0.14
OPC10 — 1	13.73	14.3	—
OPC10 — 2	13.68	14.6	—
OPC10 — 3	—	13.8	0.16
OPC10 — 4	—	14.1	0.15
OPC10 — 5	—	13.6	0.15

The average Young's modulus of samples made using the FA100 formula was 11.10 GPa based on strain gauges data, and 11.23 GPa based on extensometer data. The difference between the results was 1.17%. It confirms that both measurements were conducted correctly. Due to the greater number of measurements made using extensometer, and the highly similar results from both measurements, the average value calculated based on extensometer results was taken for further analysis, Table 3.

Table 3

Average Young's modulus values

Average Young's modulus values					
Sample	Young's modulus [GPa]	Standard deviation [GPa]	Standard deviation of the average value [GPa]	Average value [GPa]	Confidence interval [GPa]
FA100 — 1	10.0	1.5	1.3	11.2	(8.2; 14.2)
FA100 — 2	9.9				
FA100 — 3	12.4				
FA100 — 4	12.6				
OPC10 — 1	14.3	0.4	0.3	14.1	(13.4; 14.7)
OPC10 — 2	14.6				
OPC10 — 3	13.8				
OPC10 — 4	14.1				
OPC10 — 5	13.6				

Table 4 shows a comparison of Young's modulus values calculated based on original tests, and Young's modulus values calculated using formulas[3] proposed in [13]:

$$E_c = 580 \cdot f_{ck} \tag{3}$$

or

$$E_c = 0{,}037 \cdot \rho^{1,5} \cdot \sqrt{f_{ck}} \tag{4}$$

where: E_c — secant Young's modulus [MPa],
f_{ck} — sample strength [MPa],
ρ — density [kg/m^3].

These formulas were developed using generalisations and approximations of test results shown in papers [12-14] concerning samples made of various materials and using greatly differing formulas. Among others, study [14] involved varying activator types and an addition of ground blast furnace slag, while in study [12], two activator types were used, which led to marked differences between sample properties. Furthermore, in all the cases described, the samples were cured at elevated temperatures for at least 24 hours.

Table 4

Comparison of Young's modulus values from original tests and calculated based on [13]

Young's modulus [GPa]				
Original tests			Values calculated as per Diaz-Loya et al. [13]	
Sample	Strain gauge	Extensometer	As per (3)	As per (4)
FA100 — 1	11.52	10.0	15.5	20.1
FA100 — 2	10.67	9.9	15.5	20.1
FA100 — 3	—	12.4	15.5	20.5
FA100 — 4	—	12.6	15.5	20.5
OPC10 — 1	13.73	14.3	13.3	18.7
OPC10 — 2	13.68	14.6	13.3	18.7
OPC10 — 3	—	13.8	20.0	22.9
OPC10 — 4	—	14.1	20.0	22.9
OPC10 — 5	—	13.6	20.0	22.9

[3] The original symbols used by the authors of paper [13] are replaced with commonly used symbols.

Values calculated using formula (3) are closer to values achieved in the original tests. The difference compared to the average modulus value for FA100 (11.2 GPa in Table 3) is approx. 39%. For values calculated using formula (4), this difference rises to 80%. For OPC10 samples, the difference compared to values obtained using formula (3) ranges from 6% to 42%. While for values calculated using formula (4) it is greater, between 33% and 62%. The main cause of such discrepancies is the significant difference in composition and curing conditions of the samples, the properties of which served as basis for determining the formulas for calculating Young's modulus for geopolymer concrete in study [13]. Charts 1 and 2 show a comparison of results obtained in the two tests, from strain gauges and extensometer.

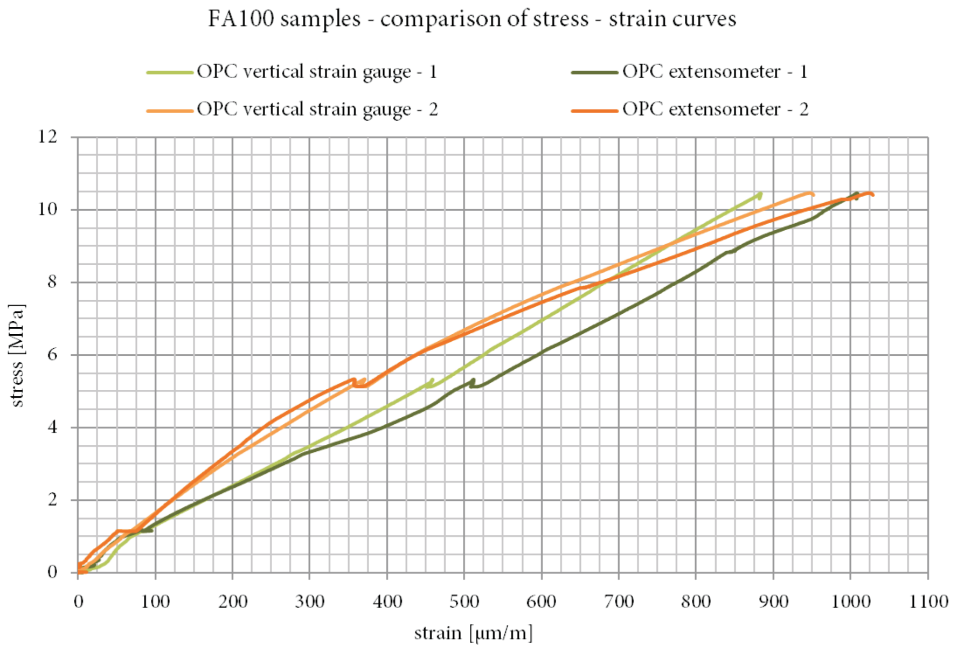

Chart 1. Comparison of stress — strain curves for FA100 samples – 1 and FA100 – 2

Strain gauge operation was characterised by faster stabilisation after reaching constant force and more stable readings during sample unloading. This is related to a greater surface area of contact between strain gauges and samples, which makes them less susceptible to local discontinuities in the form of air bubbles. For extensometer, the four-point system of contact with the sample was highly susceptible to minor changes in the external structure of the material. From this perspective, preliminary loading of extensometers was much more important. One beneficial quality of extensometers and an advantage they had over strain gauges was their lack of susceptibility to loosening of the surface layers of the concrete sample; after a minor spontaneous displacement as a result of such an occurrence, they continued to correctly record sample strain along the entire length of the measurement base. In such cases, strain gauges essentially registered the behaviour of the loosened material layer.

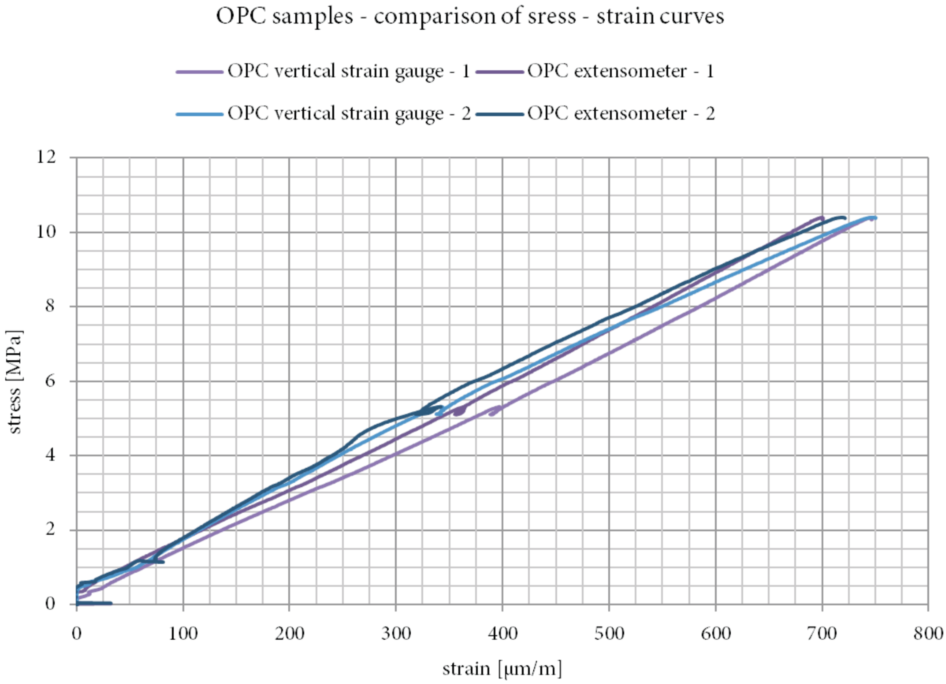

Chart 2. Comparison of stress — strain curves for OPC10 samples – 1 and OPC10 – 2

The average value of Poisson's ratio was $\nu = 0.14$. This value is consistent with the result obtained in paper [13] for sample 10, whose properties and ash composition are the most similar to samples studied in this paper.

5. Summary

The purpose of the study was to determine the values of material constants of low-calcium fly ash-based geopolymer concrete that was not subjected to additional curing at elevated temperatures during the maturation period. The experiments conducted confirm that it is possible to eliminate additional curing of geopolymer concrete at elevated temperatures during the maturation period. The results demonstrate that geopolymer concrete with cement addition (OPC10) is a more elastic and uniform material than pure geopolymer concrete (FA100). However, both test sample types exhibited lower Young's modulus values than calculated based on formulas proposed in paper [13]. Heretofore the state of knowledge on the properties of geopolymer concrete made of locally acquired components indicates a necessity of further research. It is therefore essential to conduct more in-depth studies of basic material properties, the aggressive environment effects on geopolymer concrete, frost resistance and geopolymer concrete effects on its environment. Even at the current stage of studies, the test material shows significant potential for use in construction as replacement for concrete made of Portland cement.

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Wpływ dodatku cementu portlandzkiego na moduł Younga betonu geopolimerowego z popiołu lotnego dojrzewającego w warunkach laboratoryjnych

Streszczenie. W artykule przedstawiono wyniki badań modułu Younga oraz współczynnika Poissona przeprowadzonych na próbkach wykonanych z betonu geopolimerowego na bazie popiołu lotnego niskowapiennego oraz próbkach z 10% dodatkiem cementu portlandzkiego dojrzewających w warunkach laboratoryjnych. Ponadto przedstawiono układ pomiarowy oraz metodologię wykonywania i badania próbek. Odkształcenia badano równocześnie przy użyciu tensometrów rezystancyjnych oraz ekstensometrów na próbkach walcowych o średnicy 150 mm i wysokości 300 mm.

Słowa kluczowe: budownictwo, materiały budowlane, beton geopolimerowy, moduł Younga, współczynnik Poissona

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