Strength and deformability of cement stone, mortar and concrete during loading

V T Erofeev¹*, N I Makridin², I N Maksimova², V V Moiseev¹

¹National Research Mordovia State University, 68 Bolshevistskaya str., Saransk, Russian Federation
²Penza state University of architecture and construction, 28 Herman Titov street, Penza, Russian Federation

* anna19811981@mail.ru

Abstract. The article analyzes the structural strength and the main provisions of the mechanical behavior of cement systems under short-term loading. It presents the results of the research into concrete’s strength and deformability at the structural levels of the cement stone, mortar and concrete in general during loading. To fabricate concretes, manufacturable binders, quarry sands and rock – silica clay of the Penza region were used. The following materials were considered: cement stone with different W/C, cement mortar with different sands and with its addition in different proportions, and concrete with the use of a light aggregate – thermolith. It was found that when the W/C increases from 0.25 to 0.31, the ultimate compressibility and ultimate extensibility of cement stone increases to 9% and 29.5%, respectively. The introduction of various types of sand into the composition caused the reduced compressibility and extensibility of materials, despite the fact that the mortars became more plastic. The authors describe the fabrication technology and properties of a light aggregate based on a silica clay - thermolith. Tests of thermolith concrete showed the character of immediate elastic and rapidly increasing creep deformations development in the context of longitudinal compression and transverse expansion.

Keywords: cement systems, concrete’s strength, deformability, structural levels of the cement stone, compressibility and extensibility of materials

1. Introduction
As it is known, the main objective of modern materials science is to create materials with certain properties. For construction materials of structural purpose, which includes, first of all, concrete, such property is structural strength, since the strength of cement stone and concrete is the most important indicator of the quality of their structure, which further bears on almost all other properties of these materials and, consequently, on the scope of their application [1,2,3].

The problem of concrete quality becomes particularly pressing and topical in modern economic conditions, characterized, on the one hand, by an increase in the cost of energy and material resources, and on the other, – in connection with the intensive development and practical implementation in construction practice high-quality concretes of high and particularly high strength, for which the assessment of the actual marginal states of the structure is of particular scientific and practical significance, since it is known from the mechanics of materials that high-strength materials have low crack resistance (fracture toughness) and residual strength in the presence of structural defects [4-7].

The study and design of structures is based on obtaining data on the behavior of concrete under various loads. During the test, the stresses and strains that occur in the sample as the load increases are measured and registered, and the results are expressed as stress-deformation diagrams.

By doing this, it is important to identify the influence of the main factors on the behavior of concrete under load [8-12]. There is quite a lot of such factors for composite materials, while their
specific properties are largely manifested in their heterogeneity, which is caused by the diversity of its components and manufacturing technology. The heterogeneity of concrete manifests itself at different levels of its structure: nano-, micro- and macrostructure, i.e. at the level of new growths of cement stone, products based on interacting particles of binder and fine-dispersion fillers of the composite at the level of interaction between the matrix component and fillers [13-17].

In this regard, it is important to reveal strength and deformability indicators for concretes made of local raw materials.

The paper’s objective is to study the strength and deformability of concretes made of local aggregates.

Research tasks:
1. To make a selection of local aggregates to be used in the fabrication of concrete.
2. To develop a technology for fabrication of thermolith gravel based on silica clay.
3. To single out the composition of mortars and concretes based on local aggregates.
4. To study the strength and deformation properties of cement stone, mortar and thermolith concrete under axial compression.

2. Materials and methods

Strength and stress-strain properties of cement stone, sand concrete and thermolith concrete under axial compression were studied.

To study the stress-strain properties and strength of cement stone, Sebryakov plain Portland cement with an activity of 41.5 MPa of normal density equal to 0.26 was used. As a binding agent for the fabrication of samples of fine-grained composites, we used plain Portland cement manufactured by «Bolshevik» plant, concrete grade 400 with a normal density of 26 %. For the fabrication of concrete samples, sulphate-resistant Portland cement grade 400 produced by "Bolshevik" plant in Volsk city was used.

The characteristics of cements were determined in accordance with the requirements of GOST 310.1-76, GOST 310.3-76 and GOST 310.4-81 [19, 21].

When studying sand composites, the effect of fillers of various sizes and their quantitative content we considered mixtures composed with the use of 3 types of sand. The main properties of the sands are shown in table 1.

| Sand Type  | γ, kg/m³ | Mf, Fineness modulus | W/C | Water demand by sand mass, Wd, % | C/S by mass |
|------------|----------|----------------------|-----|-------------------------------|------------|
| Sursk      | 1 540    | 1.45                 | 2.5 | 0.63                          | 0.14 < 0.14|
| Konstantinovo | 1 480    | 1.67                 | 0.8 | 1.8 8.5 35.5 95.0 100         |
| Volsk      | 1 550    | 2.7                  | 0   | 6.0 66.5 97.5 100             |

As a fine and coarse aggregate in the fabrication of concrete, Sursk river sand with a fineness modulus of Mf=1.56 and thermolith of the experimental batch were used.

Two series of cement stone samples with a W/C of 0.25 and 0.31, three series of sand composite samples and 2 series of thermolith concrete samples were fabricated and tested [17]. Samples of mortar mixtures of equal mobility were fabricated with each type of fine aggregate. The compositions of experimental samples of cement stone and fine-grained concrete are shown in table 2.
The consistency of mixtures of all series of samples, with the exception of the CS-2 series, was of normal density and was characterized by cone flow on the flow table within 168 – 172 mm in diameter. With the same workability of cement compositions, their W/C significantly differed. For conditions of equal workability, the sand water demand in the compared series of samples was estimated using Yu. M. Bazhenov formula [18]:

\[
W_d = [(W/C)_m - (W/C)_c / n] \cdot 100,
\]

where \((W/C)_c\) – water cement ratio of cement dough of normal consistency; \((W/C)_m\) – water cement ratio of mortar; \(n\) – number of parts of sand against one part of cement.

Each series of samples made of cement stone and cement-sand mortar consisted of 12 test beams in size of 40x40x160 mm. Preparation of mixtures and fabrication of samples was performed according to the methodology of GOST 310.4-81. After daily storage in forms above water, the samples were unbuttoned and placed for 27 days in a bath with water at a temperature of 20 – 22°C. Then the samples were stored in natural laboratory setting for 30 days.

To study the stress-strain and strength properties of thermolithconcrete, two compositions of concrete of grade 200 were selected, similar in terms of the workability to the concrete mix used for fabrication of reinforced concrete structures such as PTC and PNS, i.e., respectively, with a workability of 50 – 80 cm and 4 – 6 cm. The composition of 1 series concrete - compacted concrete mix with a workability of 50 – 80 cm was as follows: cement – 366 kg/m³, sand – 733 kg/m³, thermolith –650 kg/m³ (840 l/m³), water –273 l (W / C 0.746); for concrete of the 2nd series with a workability of 4 – 6 cm: cement – 400 kg/m³, sand – 640 kg/m³, thermolith – 665 kg/m³ (864 l / m³), water – 350 l (W/C 0.875).

For the study of concretes, cube-samples and prisms-samples were made with sizes of 100x100x100 mm and 100x100x400 mm, respectively. Samples were formed on a flow table with standard vibration parameters using a ballast platform of 15 gs/cm². The vibration time of the 1st series concrete mix was 100 – 120 s, and the 2nd series – 20 - 30 s. 30 cubes and 20 prisms were made on each concrete composition. A distinctive feature of light concrete thermolith mixes is a fairly rapid deterioration of its workability, which is due to the high capillary potential of the thermolith aggregate. The molded samples were exposed to heat-and-humidity treatment (HHT) in a laboratory steam chamber according to the pattern (h) 3+2+4+natural cooling at an isothermic temperature of 80°C. After HHT, the samples were stored in normal laboratory conditions.

Samples of cement stone were tested at the age of 59 – 60 days, cement-sand compositions at the age of 60 – 65 days, and thermolith concrete 28 days after heat treatment. The strength and structural characteristics of composites were estimated under monaxial short-term static compression in accordance with the recommendations [19, 20, 21]. Mechanical tests of samples were carried out using the UMM-50 compression apparatus. To measure deformations AID-1M meter was used.
Longitudinal and transverse deformations of the samples were measured under the stress state of axial compression. To do this, 50- and 30-mm load cells were pasted crosswise on each face of the prism in the middle part of its height, respectively, in the longitudinal and transverse directions. The structural, stress-strain and strength characteristics of the samples were determined under short-term loading in accordance with the recommendations [20].

After processing of strain sensor measurements, the values of the ultimate compressibility ($E_1$), the ultimate transverse extensibility ($E_2$), the coefficient of transverse deformation ($\nu$), the volume relative change of the cement stone under axial compression ($\Theta$), the volume gain ($\Delta\Theta$) were determined and based on the above values the boundaries of appearance of loose spots in the cement stone structure and the development of microcracks was estimated.

3. Results and discussion

Figure 1 shows experimental curves of longitudinal and transverse deformation of cement stone under axial compression.

![Figure 1](image)

**Figure 1.** Curve diagram of longitudinal ($\varepsilon_1$) and transverse ($\varepsilon_2$) deformations of cement stone under axial compression: 1 and 1' - at $W/C = 0.25$; 2 and 2' - at $W/C = 0.31$.

The average prism strength of cement stone with $W/C=0.25$ was 129 MPa, and cement stone with $W/C = 0.31 – 105$ MPa. As follows from the findings shown in Fig. 1, the ultimate compressibility and ultimate extensibility of cement stone increased with an increase in $W/C$ in the range from 0.25 to 0.31. Moreover, the increase in deformability was about 9 and 29.5%, respectively, that is, an increase in the $W/C$ ratio in the considered range significantly increases the transverse extensibility of the cement stone.

When aggregates are added to the composition of cement mixtures, the deformability reduces. The character of destruction of samples under axial compression as the sand composition increases becomes more plastic, despite the fact that the ultimate compressibility and transverse extensibility of the material decreases, as can be seen in the graphs of figure 2 - 4.

The problem of aggregates for the manufacture of structural concrete in construction engineering is pressing, since there are no deposits of rocks suitable for the production of dense (coarse) aggregates in certain territories. The existing production of expanded clay gravel does not meet the modern requirements of the market economy due to the lack of high-quality clay raw materials.

In this regard, a very prospective local raw material for the production of artificial porous aggregate for the fabrication of light structural concrete is siliceous rock (silica clay/opoka), the deposits of
which in the Penza region, according to [22], are rather profound. The chemical composition of the silica clay is as follows, %: SiO₂ - 84.88; Al₂O₃ - 4.6; Fe₂O₃ - 3.12; TiO₂ - 0.12; CaO - 0.38; MgO - 1.05; SO₃ - 0.53; R₂O - 0.24; PPP - 2.10; organic substances - 2.98. The main physical and mechanical properties of the thermolith made from silica clay, obtained by us, are shown in table 3.

**Figure 2.** Deformability of 1:1 sand concrete mix on various sands under short-term axial compression loading: a – Konstantinovo quarry sand; b – Sursk river sand; c - Volsk standard sand; 1 and 1’ respectively, longitudinal (ε₁₁IM) and transverse (ε₂₂IM) relative creep short-term deformation; 2 and 2’, respectively, longitudinal (ε₁₁YM) and transverse (ε₂₂YM) relative immediate elastic deformation; 3 and 3’, respectively, longitudinal (ε₁) and transverse (ε₂) relative total deformation.

To study the deformation and strength properties of structural thermolith concrete, and to receive an experimental batch of pre-stressed hollow and ribbed slabs of a PTC and NTC type in the industrial environment we fabricated a pilot batch of thermolith crushed stone based on local silica clay taken from Kanaevskoe Deposit in the amount of 15 m³.

The silica clay was fired in a keramsit kiln at a temperature of 1.070 – 1.100 °C. Thermolith aggregate fraction of 5 – 20 mm was characterized by the following values: bulk mass of 770 kg / m³; aggregate strength in a steel cylinder with a diameter of 150 mm – 8.0 MPa; water absorption in water
was 30% by weight during 24 hours and 24% - in 1 min; a number of other characteristics of the aggregate are shown in table 3.

Figure 3. Deformability of 1:2 sand concrete mix on various sands under short-term axial compression loading: a – Konstantinovo quarry sand; b – Sursk river sand; c – Volsk standard sand; 1 and 1’ respectively $\varepsilon_{1\text{IM}}$ and $\varepsilon_{2\text{IM}}$; 2 and 2’ respectively $\varepsilon_{1\text{YM}}$ and $\varepsilon_{2\text{YM}}$; 3 and 3’ respectively $\varepsilon_1$ and $\varepsilon_2$.

Mechanical tests of cubes and prisms samples at the age of 28 days showed that the ratio of prism strength to cubic one is 0.75 – 0.8, which is within the values typical for light concretes on other types of porous aggregates.

Figure 5 shows the main parameters of the mechanical behavior of structural thermolith concrete with a prism strength of 19 MPa on average at the age of 28 days at the short-term loading to failure with a five-minute delay at each loading stage. Estimation of structural and strength characteristics of concrete was carried out in compliance with the methodological guidelines [20]. To measure the deformations of thermolith concrete in the longitudinal and transverse directions, we used stationary clock-type indicators mounted on prisms graduated in 0.01 and 0.002 mm, respectively, for longitudinal and transverse deformations.
Figure 4. Deformability of 1:3 sand concrete mix on various sands under short-term axial compression loading: a – Konstantinovo quarry sand; b – Sursk river sand; c – Volsk standard sand; 1 and 1’ respectively \( \varepsilon_{\text{IM1}} \) and \( \varepsilon_{\text{IM2}} \); 2 and 2 respectively \( \varepsilon_{\text{YM1}} \) and \( \varepsilon_{\text{YM2}} \); 3 and 3’ respectively \( \varepsilon_{1} \) and \( \varepsilon_{2} \).

Table 3. Physical and mechanical properties of raw and burnt silica clay

| Properties                              | Unit of measurement | raw            | burned          |
|-----------------------------------------|--------------------|----------------|-----------------|
| Bulk density in a piece                 | g/cm\(^3\)         | 1.51±0.03      | 1.43±0.105      |
| Pycnometric density                     | –/–                | 2.02–2.40      | 2.32            |
| Water absorption by weight/mass         | %                  | 16.9±5.61      | 14.1±1.68       |
| Water absorption by weight/mass during 48 hours | –/–              | 23.9±5.03      | –               |
| Strength at axial compression           | MPa                | 45.88±5.03     | 47.37±7.85      |
| Softening ratio                         |                    | 0.63           | 0.80            |
Softening ratio during 48 hours of water absorption

| Parameter                                      | Value     |
|-----------------------------------------------|-----------|
| Initial tangent modulus of elasticity at \( \eta=0.2R \) | 11128±4544 MPa | 4984±1201 |
| Modulus of deformation at \( \eta=0.9R \)      | -100-     | 9418±3188 | 5902±1034 |
| Modulus of compression at \( \eta=0.9R \)      | mm/m      | 4.434±1.676 | 6.593±0.682 |
| Bulk fire shrinkage                            | %         | –         | 5.02±0.82  |

**Figure 5.** Graphs of changes in relative deformations (a), relative volume \( \theta \) or its gain \( \Delta \theta \) (b), Poisson’s coefficient \( v \) or its gain \( \Delta v \) (c) thermolith concrete depending on the loading degree

Figure 5 clearly shows the development of immediate elastic and rapidly increasing creep deformations of both longitudinal compression and transverse expansion of samples.

Comparing thermolith aggregate with expanded clay, we can talk about a significant advantage of thermolith aggregate in terms of strength. As for the elastic properties, an objective judgment can be made based on the results of testing of thermolith and expanded clay cements. The experiments findings allow us to judge on the thermolith deformation characteristics and compare it with other artificial coarse porous aggregates by the elastic modulus index which is one of the most important structural characteristics of aggregates for structural purposes, and also they make it possible to take a more reasonably approach to the design of the thermolith concrete composition.

### 4. Conclusion

1. The paper imparts the latest developments on the strength and deformability of concretes made of local aggregates.
2. The sands of Konstantinovo, Sursk and Volsk quarries of the Penza region of the Russian Federation were selected as fine aggregates.
3. The authors describe the technology for producing thermolith gravel based on local silica clay with improved properties compared to expanded clay.
4. Deformability diagrams were obtained for various structural levels of concrete: cement stone, mortar, and concrete itself.
5. It was found that for cement stone with the W/C ratio increase from 0.25 to 0.31, the increase in the ultimate compressibility and ultimate extensibility was, respectively, about 9% and 29.5%.

6. Testing of mortar samples shows that as their sand component increases, the material becomes more plastic, despite the fact that the ultimate compressibility and transverse extensibility of the material decreases.

7. A technology for producing thermolith concrete has been developed with effective compositions on its basis; the deformability of concretes based on mixtures of different flow has been studied. When testing samples for compression, the character of development of immediate elastic and fast-flowing creep deformations of both longitudinal compression and transverse expansion of samples has been revealed.

5. References

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