eJSE International

Electronic Journal of Structural Engineering, 6 (2006)

The effects of sulfate solution on the behavior of reinforced concrete beams

Behrouz Mohebimoghaddam

Department of Civil Engineering, Islamshahr Azad University
Division of Retrofitting of Existing Structures in National Land and Housing Organization
Tehran, Iran
e-mail: bmohebi@hotmail.com.

ABSTRACT: Reinforced concrete structures can be adversely affected by chemical aggressive environments such as sulfates and chlorides. It is necessary to study the durability and some other critical engineering properties of these structures in such environments. The paper in hand reports the experimental results of sodium sulfate solution influence on the physical and mechanical properties of normal strength concrete. The experimental work included 18 reinforced concrete beams (2300×60×100 mm^3). The beams loaded at the mid span following a two point loading setup. Three kinds of environments were chosen for curing the beams prior to testing: state temperature and humidity standard conditions, water basin and sodium sulfate solution. The curing environments were applied to the beams from three sides. The flexural strength and stiffness, inelastic strain in concrete, crack width and deflection were measured. The experimental results presented in this paper clearly indicate that the reinforced concrete beams exposed to sulfate solution causes a decrease the flexural strength and stiffness and an increase the width of flexural cracks.

Keywords: Crack, Deflection, Stiffness, Strain, Sulfate solution

1. INTRODUCTION

Since vast number of structures such as industrial, marine and reservoirs structures are affected by chemical attacks, studies regarding to the influences of these chemicals on structural integrity of reinforced concrete (RC) elements are necessary. Previous studies have often carried out on one-span beams which were attacked by aggressive environment from one side [5], [3]. In this matter of fact for finding the effect of aggressive environment on cross sections in mid span and support, two-span RC beams were chosen and for more precise result, they were affected through triple sided aggressive environment.

The previous experimental results have shown that influence of sulfate solution with different concentrations in long term can cause a decrease in the flexural strength of beam up to 20% [6]. According to Ref. [12], strength of cross sections with low reinforcement ratio (ρ = 0.89%), medium (ρ = 1.8%) and high (ρ = 2.79%) in 480 days of exposure to sulfate solution of 5% sodium sulfate solution were respectively decreased to 5.6%, 11% and 14%.

This paper introduces the testing of 6 beams during 18 months with 3 different curing conditions. In these conditions, the physical and mechanical behavior of beams was studied. The main parameters which are discussed in this paper are the strength of RC beams, strain in the compression zone of concrete and in the steel reinforcing bars, width of the cracks, flexural stiffness and deflection. For all main parameters, a comparison was done between specimens with different reinforcement ratio and curing conditions (with and without influence of aggressive environment). In this investigation, the author has only mentioned the influence of sulfate solution on concrete.

2. RESEARCH SIGNIFICANCE

In situ conditions, structural members such as beams can be affected through exposure to aggressive environment and external loading. In this paper the experimental results of the flexural beams which were exposed from three sides to the sodium sulfate solution are reported.

3. ANALYTICAL INVESTIGATION

Aggressive environments cause a decrease of durability and load capacity of structural members. In previous study, to consider the long term effect of sulfate solution on flexural strength of beams the following expression was used [4]:

$$M_u(t) = 0{,}85.f'c(t).a(t).b(t).[d(t) - \frac{a(t)}{2}] + A'_s.f_y.[d(t) + d'(t)] \qquad (1),$$

where M_u is ultimate flexural strength of RC beams; a is depth of equivalent rectangular stress block; b and d are the width and the effective depth of cross section of beam; d' is the distance from extreme compression fiber to compression reinforcement; f'_c is compressive strength of concrete as a function of time; A'_s is area of compression reinforcement and f_y is yield strength of reinforcement.

Compressive strength of concrete f'_c may be expressed as [10], [11]:

$$f'_c(t) = \gamma_m(t).\gamma_h(t).\gamma_e(t).\gamma_l(t).f'_c \qquad (2),$$

where γ_m is coefficient for considering the effect of humidity on decreasing of concrete strength and is evaluated as Ref. [11]; γ_h is coefficient for considering the effect of cement paste hydration process and is evaluated as Ref. [11]; γ_e is coefficient for considering the effect of active components of environment and is evaluated as Ref. [11]; γ_l is coefficient for considering the effect of load procedure on concrete strength and is evaluated as Ref. [11].

Flexural stiffness before and after cracking can be expressed as:

Before cracking ($M<M_{cr}$) [14]:

$$B_{cr}(t) = 0{,}85.E_b(t).I_{red}(t) \qquad (3),$$

where B_{cr} is flexural stiffness of cross sections before cracking; E_b is modulus of elasticity of concrete and is evaluated as Ref. [4]; I_{red} is moment of inertia of modified cross section and is evaluated as Ref. [4].

After cracking ($M \geq M_{cr}$) [1], [4]:

$$B(t) = \frac{d(t).z(t)}{\dfrac{\psi_S}{E_S.A_S} + \dfrac{\psi_b}{[\varphi_f(t) + \xi(t)].b(t).d(t).E_b(t).\nu_b(t)}} \qquad (4),$$

where z is the distance from center surface of steel bars till resultant point of internal forces in compression zone above the cracks and is evaluated as Ref. [4]; ψ_S is a coefficient for tension concrete at points with cracks and is evaluated as Ref. [1]; φ_f is a coefficient evaluated as Ref. [1]; $\xi(t)=x(t)/d(t)$, proportional depth of compression zone of concrete; x is depth of compression zone of concrete; E_s is elasticity modulus of tension steel bars; ψ_b=0.9;

v_b=0.45 when $M \le M_u$ otherwise is evaluated as Ref. [5].

Deflection of mid span of beam is expressed as [2]:

$$f = \sum_{i=1}^{n} \int_{l} \overline{M}_i(s).\frac{1}{r_i}(s).ds, \quad (5),$$

where n is number of divisions with constant flexural stiffness; $M_i(s)$ is bending moment when P=1; $1/r_i(s)$ is curvature.

4. EXPERIMENTAL INVESTIGATION

The beam geometry and reinforcement details, the position of loading and supports are illustrated in Fig. 1.

The point load was applied on the upper edge of the beam, at the mid spans. According to placement of reinforcements, test specimens were classified into three groups (section 1-1, section 2-2 of Fig. 1 and Table 1).

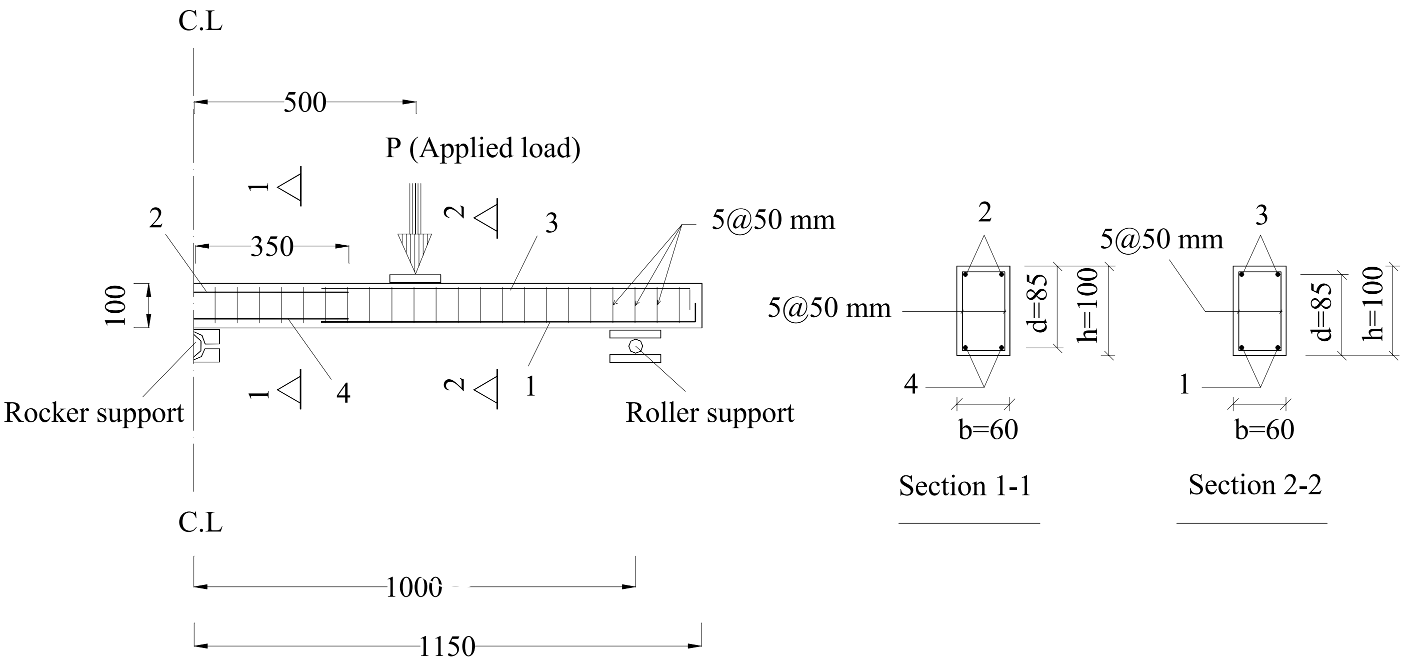

Figure 1: Geometrical dimensions and reinforcement (all dimensions in mm).

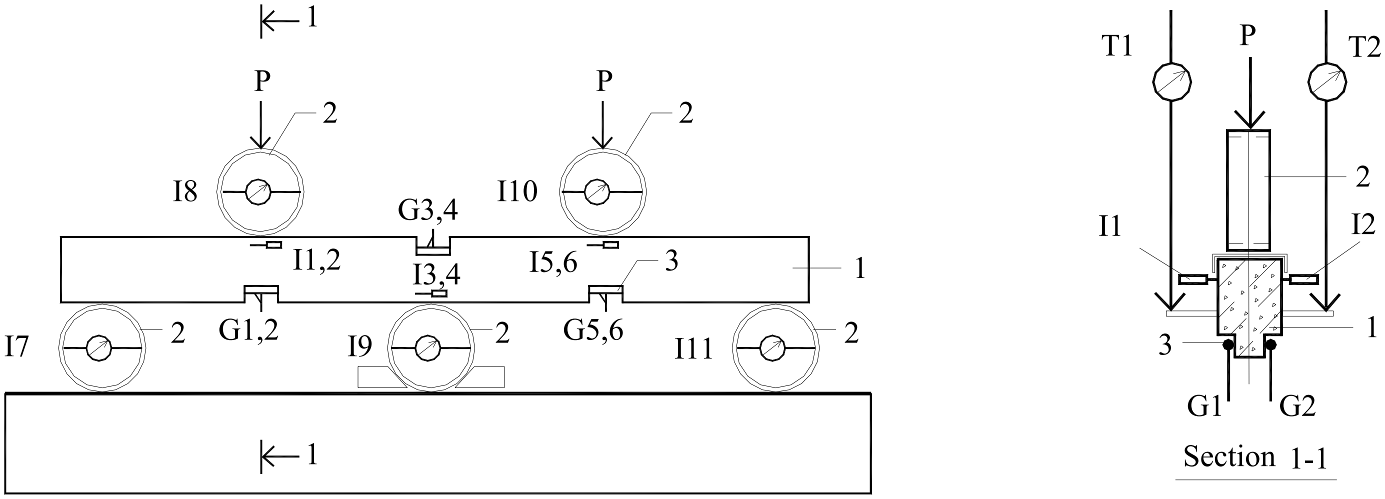

Figure 2. Test setup: 1- Reinforced concrete beam; 2 – Steel rings; I1-6=indicator for measurement of strain in concrete; I7-11=indicator for measurement of reactions and applied loads; G-gauge for measurement of strain in steel bars; D-linear differential transformers for measurement of deflection.

Table 1. Reinforcement of test beams

Diameter (mm), Quantity and class of steel bars					
Bars position					
Group no.	1	2	3	4	5
1	2ϕ6 A–I	2ϕ6 A–I	2ϕ6 A–I	2ϕ3 A–I	2ϕ3 A–I
2	2ϕ10 A–III	2ϕ3 A-I	2ϕ6 A–I	2ϕ3 A–I	2ϕ3 A–I
3	2ϕ10 A–III	2ϕ6 A–I	2ϕ10 A–III	2ϕ3 A–I	2ϕ3 A–I

Considering the aggressive environment test specimens were sub-classified into three groups: Group A was cured in standard heat-humid conditions according to Standard SNiP 2.03.11-85 1989 Ref. [13], Group B was immersed in a water basin and Group C was immersed in sulfate solution of 5% concentration. In situ conditions were represented approximately by lower concentrations up to 0.5%. The higher concentration was chosen to accelerate concrete deterioration process.

According to three curing conditions and three placements of reinforcement, 18 beams were tested. For the sake of briefness, the results of 6 beams are presented here.

4.1. Material properties

Ordinary Portland cement with a 8 mm maximum coarse aggregate size and fine aggregate (medium-sized natural sand) with cement/sand/coarse aggregate ratio equals to 400:600:1300 and water/cement ratio of 0.5 were used for preparation of concrete mixture.

All ingredients were mixed in a concrete mixer for about 4 minutes. Then they were poured into 18 wooden molds. The beams were then placed on a vibrator table for casting. Thirty concrete cubes (100×100×100 mm^3) were also cast for testing the compressive strength of the specimens. The concrete specimens and cubes were cured in the moulds and covered with burlap at 20°C for 48 hours. Then they were demolded and kept in a standard curing room for 28 days. 28-days cured specimens had an average strength of 25 MPa. After 180 days the beams were loaded by jack at mid span.

4.2. Testing procedure

Beams were composed of two equal spans of 1000 mm each, and were loaded as shown in Fig. 1. Steel rings were used to measure the reactions of supports, and special gauges were attached to steel bars at the bottom of mid spans and over central support to measure strain in concrete and in steel bars. Linear differential transformers were used for measurement of mid spans deflection (see Fig. 2). The level of loading before cracking was 10% of expected cracking load and after cracking 20% of expected ultimate load. During experiment, reactions of supports and deflections in mid of each span were estimated and widths of cracks, strain in steel bars and in compression zone of concrete were measured. In all stages of testing, the beams were removed from sulfate solution and water basin.

5. EXPERIMENTAL RESULTS AND DISCUSSION

The previous experimental researches show that as a result of effect of aggressive environment, width and depth of beams cross section decrease with time [7], [8], [9].

In present investigation, the beams are affected by sodium sulfate solution from three sides. Due to compression zone of cross sections in mid span and central support of beam that are placed respectively above and bottom of neutral axis, compression zone of concrete in cross sections of central support are affected by aggressive environment from two sides and in cross sections of mid spans from three sides (see Fig. 1). So the depth (h) and width (b) of cross sections at whole point of beams and effective depth (d) of cross sections in central support of beams are being decreased, but effective depth of cross sections in mid span is not being changed. Therefore there was seen some differences in effect of aggressive environment on the flexural strength and also other mechanical factors.

Changes in bending moment M at mid spans and support of A-2, B-2, C-2 beams are shown in Fig. 3.

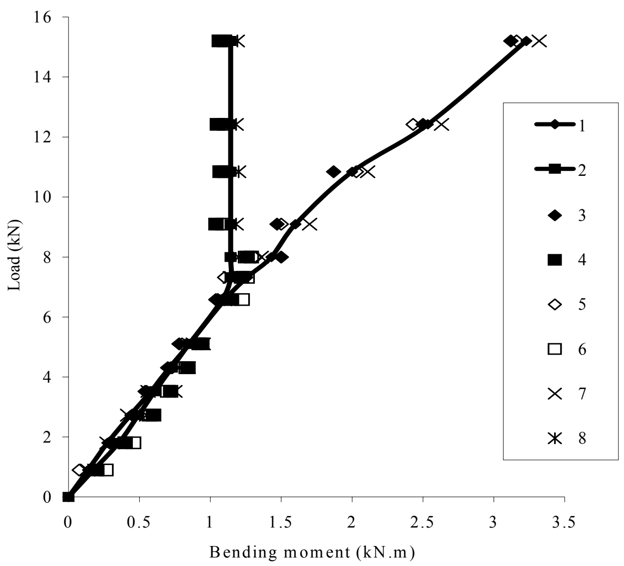

Figure 3: Load versus bending moment in cross sections of mid span (1, 3, 5, 7) and central support (2, 4, 6, 8). Analytical quantities (1, 2); experimental quantities: A-2 (3, 4), C-2 (5, 6) and B-2 (7, 8).

The experimental results implied that the flexural strength of beams with lower reinforcement ratio (ρ=1.1%) and beams with higher reinforcement ratio (ρ=3.1%) are decreased by 4% and 14.8%, respectively, after 18 months exposure to sodium sulfate solution (see Fig. 3). It can be explained as flexural strength in cross sections with lower reinforcement ratio is limited through steel.

Both analytical and experimental results show that the flexural strength of beams at mid span decreases significantly more than that of beams at central support when subject to sodium sulfate solution during 18 months.

Fig. 4 shows the ratio of bending moment and ultimate resisting moment M/M_u versus strain in tensile steel bars and in compression zone of concrete at central support of A-2 and C-2 beams. The result demonstrates that the strain in C-2 beams which are subject to sulfate solution is 25% higher than A-2 beams.

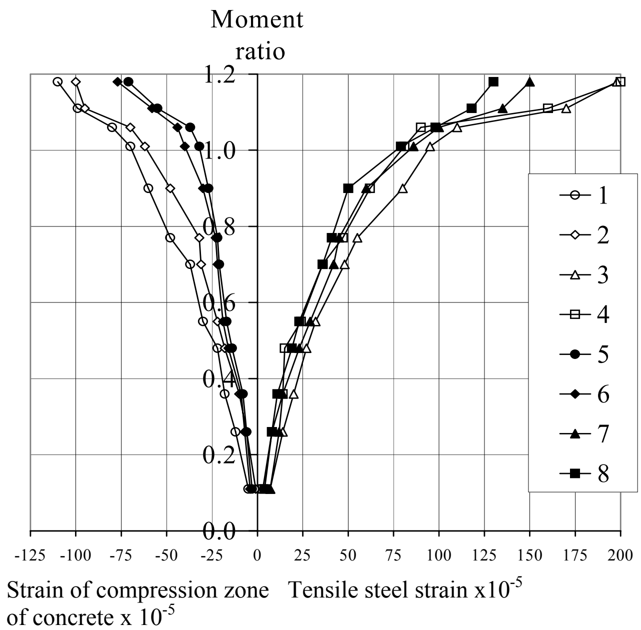

Figure 4: Moment ratio versus strain of tensile steel bar (1, 2, 5, 6) and compression zone of concrete (3, 4, 7, 8) over central support of beams C-2 (1, 2, 3, 4) and A-2 (5, 6, 7, 8).

Fine cracks were observed soon after application of the load. Width of cracks in different points of beams was measured. Fig. 5 shows the changes of crack width versus M/M_u of beams A-2, B-2 and C-2. As expected, the crack width increases with the increasing application of load till making plastic hinge. The results infer that curing in sulfate solution has the most adverse effect on the crack width of beams (as shown by largest crack width measured on beams C-2).

The crack width on beams with lower yield strength (steel bars class A-I, $F_y \approx 215$ N/mm^2) increases significantly more than that on beams with higher yield strength (steel bars class A-III ($F_y \approx 390$ N/mm^2).

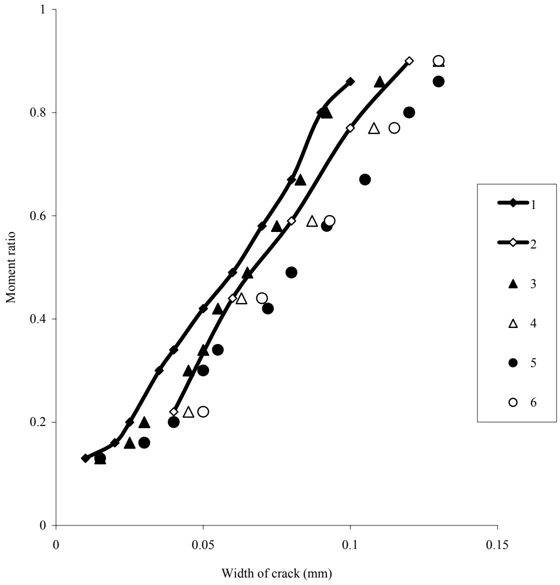

Figure 5: Moment ratio versus width of cracks A-2 (1, 2), C-2 (3, 4) and B-2 (5, 6) beams; in mid span (1, 3, 5); over central support (2, 4, 6).

Fig. 6 shows the distribution of flexural stiffness of A-2 and C-2 beams. As expected through analytical studies, it was indicated that the flexural stiffness at central support is more than that at mid span before cracking occurs. Although after cracking, the before decreasing rate of flexural stiffness at central support was higher than that at mid spans. Flexural stiffness of C-2 beams after 18 months in sulfate solution at both mid span and support cross sections was lower than flexural stiffness of A-2 beams.

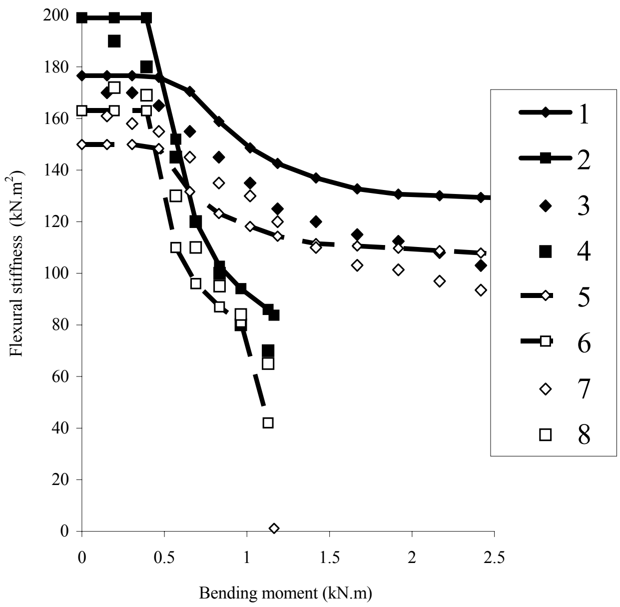

Figure 6: Distribution of flexural stiffness of A-1 (1, 2, 3, 4) and C-1 (5, 6, 7, 8) beams: analytical quantities (1, 2, 5, 6); experimental quantities (3, 4, 7, 8); in spans (1, 3, 5, 7); over central supports (2, 4, 6, 8).

Fig. 7 shows the relation between applied load versus mid span deflection of A-2, B-2 and C-2 beams. The deflection of beams B-2 (cured in water) and C-2 (cured in Sulfate solution) were higher by 15% and 36% respectively than beams A-2 (cured in standard humid condition). The difference in beam deflections is also observed in loading level approximately equal to 40% - 60% of failure load.

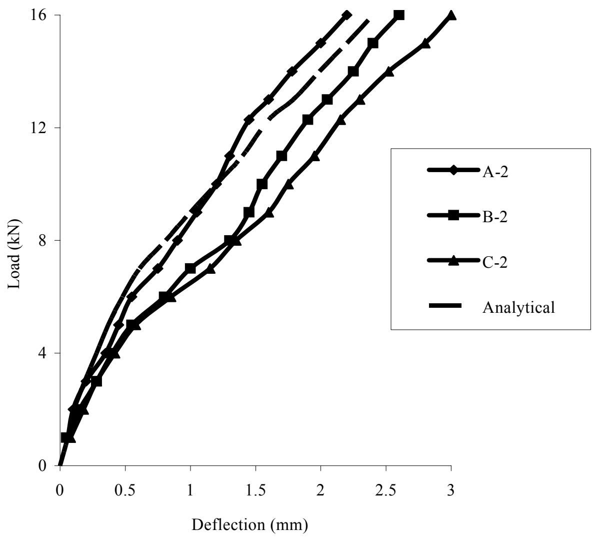

Figure 7: Load versus deflection of A-2, B-2, C-2 beams and analytical quantities.

6. CONCLUSION

Based on the experimental and analytical results reported in this paper, the following conclusions are drawn:

- Considerable difference was observed between deflection of all of the immersed beams in sulfate solution and beams which were cured in heat-humid standard conditions.
- The effective depth of beams exposed to sodium sulfate solution at the central support were decreased and as result, the flexural strength of the cross section decreased more than that at mid span of the beam.
- The experimental results indicated that higher reduction in flexural stiffness was observed in beams with higher reinforcement ratio.
- Width of crack was higher in cross sections with steel bars A-III class compared to same sections with steel bars A-I class.
- Before cracking, the flexural stiffness of cross sections in central support was higher than that of mid spans. But after cracking, the flexural stiffness of cross sections in central support was significantly lower than that of mid spans.

7. ACKNOWLEDGMENTS

This study was conducted in the department of "Reinforced concrete and stone structures" of Pridneprovsk state academy of civil engineering and architecture in Ukraine. The author would like to thank Pridneprovsk Research Laboratory of Ukraine for their support.

8. REFERENCES

[1] Bairamoukov, S., 1999, "Change of flexural stiffness of beams at time t," *Concrete and Reinforced concrete*, №2, pp. 15-17.
[2] Bairamoukov, S., 1999, "Deflection of beam at time t," Concrete and Reinforced concrete, №4, pp. 25-28.
[3] Berke N.S., D.W. Pfeifer and T.G. Weil, 1988, "Protection against chloride-induced corrosion." Concrete International 10(12), pp. 45-55.
[4] Mohebimoghaddam, B., and Borodin, A., 2001, "Strength of reinforced concrete beams influenced by agressive environments," *Pridneprovsk state academy of civil engineering and architecture.* Dnipropetrovsk, Ukraine, 2001– № 11, pp. 13-19.
[5] Alekseev, S., 1988, "The corrosion stability of concrete, reinforced concrete and reinforced bars in aggressive environments," Moscow, Russia.
[6] Alekseev, S., Ivanov, F., Modri, S., and Shissel, P., 1990, "Durability of reinforced concrete in aggressive environment," Moscow, Russia.
[7] Biczok, 1964, "Concrete Corrosion and Concrete Protection", Akademiai Kiado, Publishing House of the Hungarian Academy of Sciences, Budapest.
[8] Guzeev, E., Savitski, N., and Titiuk, A., 1990, "Computation of stress-strain relations at cross section of reinforced concrete structures with consideration of concrete corrosion kinetics," Moscow, Russia.
[9] Moskvin, V., Ivanov, F., Alekseev, S., and Guzeev, E., 1980, "Corrosion of concrete and reinforced concrete structures," Moscow, Russia.
[10] Litvinenko, D., 1996, "Corrosion of bending reinforcement concrete elements influenced by barium sulfate solution," Ph.D. dissertation, Dnipropetrovsk, Ukraine.
[11] Savitski, N., 1993, "Principles of reinforced concrete structures safety calculations in aggressive environments," Ph.D dissertation. Moscow, Russia.
[12] Titiuk, A., 1990, "Durability of bending reinforced concrete in aqueous sulfate solutions," Ph.D dissertation, Moscow, Russia.
[13] Standard codes for designing SNiP 2.03.11-85, 1989, "Concrete and reinforced concrete," Moscow, Russia.
[14] Standard codes for designing SNiP 2.03.11-85, 1986, "Corrosion of reinforced concrete," Moscow, Russia.