**13th World Conference on Earthquake Engineering**
**Vancouver, B.C.,Canada**
**August 1-6, 2004**
**Paper No. 2182**

# SEISMIC PERFORMANCE CAPACITIES OF OLD CONCRETE

**Vsevolod LEVTCHITCH[1], Victor KVASHA[2], Helen BOUSSALIS[3], Anastasios CHASSIAKOS[4] and Elias KOSMATOPOULOS[5]**

**SUMMERY**

Static, dynamic and low cycle fatigue testing of 20…30 years old concrete have been carried out. Samples were taken from residential buildings in Cyprus and bridges in Ukraine. Dynamic strengthening factors were 2…4 times lower than those of 28 day concrete. Dynamic strengthening in splitting has been approximately 4 times smaller than that in compression. The static tensile-to-compressive strength ratio of old concrete is more than two times lower than that of young concrete. Modulus of elasticity is increasing with age more significantly than the strength. Elasticity modulus increase has been observed even in cases when there was no increase of strength. Ultimate strains were drastically lower than those of a young concrete. A reduction of approximately 50% has been observed. Up to the stress of 75% of a peak value, old concrete behaves as an elastic material.

All these changes in properties are on the alarmingly unsafe side in terms of seismic performance. Concrete with age is evidently getting to be more rigid, less ductile and exhibits a very unhappy tendency to brittle explosive modes of failure. It is becoming seismically fragile .and is an easy target for seismic forces. Old concrete itself is an object of destruction and it triggers damage and destruction of other elements. Contribution of old concrete in resisting shear and torsion is diminishing drastically. Due to a very limited ability to expand laterally, the effectiveness of confinement is also reducing and ultimately cease to have any positive effect. Low cycle fatigue capacity, i.e. seismic capacity, is totally dependant on the available reserve of plastic deformations. Only concrete with a remaining capacity to undergo plastic deformations is able to develop dynamic strengthening and provide a predictable resistance to cyclic loading. Large strength increases, commonly adopted in seismic analysis are absolutely not relevant to the actual phenomenon.

## INTRODUCTION

Old concrete is a mess. At an age of 20…30 years it is not the same material as it was at 28days. It is not just a common mix of bad and good, but a store of bad dynamic properties. In old concrete everything is changing with the course of time, but nothing is getting better, except a possible increase of static short-term compressive strength, which, in itself, is practically of no importance for the dynamic performance.

[1] Professor, Frederick Institute of Technology, Nicosia, Cyprus. savvas@research.fit.ac.cy
[2] Professor, National University- Lvivska Polytechnica, Lviv, Ukraine. salus@icmp.lviv.ua
[3] Professor, Department Chair, California State University, LA, USA. hboussa@exchange.calstatela.edu
[4] Professor, California State University, Long Beach, USA. achassk@csulb.edu
[5] Professor, University of Crete, Khania, Greece. kosmatop@dssl.tuc.gr

All dynamic characteristics keep continuously deteriorating with age. The gap between dynamic capacities of old and young concrete is quietly widening with time and the problem is continuously growing worse. Our tendency to ignore the time factor is all wrong. Basically, we have been acting as if the age just does not matter. This popular misconception about concrete age influence had stayed around for years. No matter how advanced and accurate the methods of analysis are, the outcome is totally dependent on the accuracy of input characteristics of materials. No reliable solution can be obtained if it is based on flippant assumptions. The source and cause of innumerable problems are wrongly adopted concrete properties. Henry Degenkolb put it in the following way: "If you start off on the right path, it is not hard to do things right."

In practice there is no respect to concrete age. In spite of drastic change of properties with age, there is no real attention to aging concrete . The age of concrete is largely ignored. Nobody, except a few enthusiasts, is keeping a close eye on actual capacities, remaining reserves and life expectancy of old concrete. Existing research can offer very little helpful information regarding seismic performance of old concrete. To take a calculated risk we need to know both the remaining strength and strain capacities. Practical engineering is facing a veritable jungle of contradicting information and continuously suffers from the evident lack of authoritative guidance and instruction. Although the best ever, unique 50 years investigations on long-term properties of concrete have been initiated as far back as 1910 by M. Withey [1] and successfully continued and expanded by G. Washa and K. Wendt [2], they were not followed by more recent research. Generally, the old concrete is very rarely an object of contemporary direct investigations. It remains largely unstudied neither experimentally nor analytically. Only sporadic reports about old concrete problems have been published and it looks as if this problem is already comprehensively solved. In reality it is continuously aggravating and getting more and more hot.
The main bulk of the existing building stock is old and it is getting even older, because the annual increase of new structures constitutes only (1…2)%. Due to this phenomenon the activity of construction companies is visibly shifting from the new construction to reconstruction, renovation, refurbishment, repairing, upgrading and maintenance.

Experimental, observational and analytical information on properties of old concrete is very limited , obscure, contradictory and confusing. At present it does not allow for any reliable generalization. Some properties of old concrete have been borrowed from younger concrete. For example, a very appealing , but conceptually wrong assumption that the dynamic ultimate strains can be taken the same as static values has been stretched to old concrete. It seems that this was simply done due to the lack of any better information. This is a curious and embarrassing turn because the basic differences between static, dynamic and cyclic performance have been known from the very early period of reinforced concrete, namely, from the end of 19$^{th}$ and beginning of 20$^{th}$ centuries. The fundamental difference between static and dynamic behaviour is in delaying of plastic strains development and in a steeper and shorter descending branch of the stress-strain curve. So, a reduced ultimate strains are to be expected. It follows also from the basic principle of energy conservation. But in reality there are arguments and experimental findings on both sides. In any case it is already a firmly established fact that the plastic strain capacity of old concrete is considerably lower than that of young concrete. This phenomenon has far reaching consequences.

Contemporary seismic analysis revolves around residual deformations and ability to absorb, damp and dissipate seismic energy. The inelastic behaviour of concrete was first recognized by W. Ritter in 1899 , A. Talbot in 1904 and I. Woolson in 1905 . At that time the rheologic behaviour was considered as a plague of concrete. An accurate prediction of it is still elusive. Far too many factors are coming into play. Some of them are stochastically independent , but majority are interrelated and interacting. In spite of this the earthquake analysis operates with very large displacements , just short of collapse. The influence of plastic strains is decisive for the seismic performance and survive-ability of structures.

As we see it now neither strength nor deform-ability has any physical sense if the rate of loading is not specified. They are not the physical constants and depend on embarrassingly wide range of factors. The root problem is that all of them are dependent on age, history of loading and environmental conditions. These effects are virtually inseparable. They cannot be dissociated from each other. It is not only the age factor that matter. Multi-functional dependence makes concrete to be widely varying. The history of loading and environmental characteristics cannot be modeled in any accurate way. Sustained, dynamic and cyclic loading and environmental conditions can tremendously accelerate the aging, deterioration and destruction of concrete. This problem is as old as the concrete itself. In 1899 W. Ritter was the first to suggest the compression diagram depending on loading rate. Time factor complicates the stress-strain relationship a lot. Strains can continue to increase even after 30 years of loading, but at the same time the creep strains developed during he first two years may constitute up to 85% of the total value accumulated over 20 years, Troxell et al [3]. A. Gvozdev [4] has reported a similar rate of creep over the period of 10 years under the stresses of (70-78)% of the ultimate value. In many investigations the final value of creep had been attained during relatively short periods of time: 2.5-3years -R L'Hermite[5], 3.5 years- Y. Guyon [6], 21.3 years- A. Caquot [6], 30 years- F. Kong and R. Evans[7], and G. Troxell, J. Raphael, R. Davis [3]. Right from this an extremely important conclusion can be drawn. Somewhere between 2.5 and 30 years of service life , concrete can develop its ultimate value of residual strains , can become brittle and lose its ability for the dynamic strengthening and drastically reduce its fatigue resistance.

Total-to-initial strain ratio had been found to be within the range from 3 to 5, L'Hermite [15], E. Freyssinet [8], B. Le Camus [9]. If concrete alone can provide for this large ductility, the reinforced concrete is definitely capable of considerably larger values.

The history of loading can have a dramatic effect and change concrete performance in every detail. Le Camus [9] has found that after 1000 days under sustained stress of 10MPa the following 3 million cycles of loading with the same maximum stress had resulted only in 6% increase of creep. Similar results have been obtained under the stress of 5 MPa. From this a stern warning is to follow. Concrete which adapts to sustained loading is losing its ability to develop plastic deformations under the subsequent cyclic loading.
The same author has reported a stark difference in the rate of creep under cyclic and sustained loading. 14 days of cyclic loading (11 mln cycles) had produced the same creep strain as 600 days of sustained loading with the same stress level.

The recent shift from the force controlled methods of analysis to the deformation governed philosophy requires much more intelligent use of material properties than it was before. Deformation demands and available capacities are supposed to be defined securely. The technical basis which needs years of investigations is to be vastly expanded.

## TEST PARTICULARS

### Experimental Specimens

Cylindrical core samples have been drilled from three residential buildings in Nicosia (Cyprus) and a precast bridge in Lviv (Ukraine). Two buildings were 23 years old and the third -25 years. At the moment of sampling the bridge was 30 years old. All buildings were of the same structural arrangement. They have been constructed to accommodate refugees after the events of 1974. Due to the exceptional circumstances there were practically no neither inspection of design and specifications nor materials and workmanship quality control. Two buildings have been constructed during a hot summer period and concrete was left without proper curing and protection against direct sun and wind. This resulted in a much higher variability of properties as compared to those taken from a building constructed during winter time. Moreover, buildings were designed and detailed only for the gravitational loads. Seismic codes have not been yet adopted. During their service life these buildings have been subjected to several low intensity earthquakes. Although there was no critical damage there has been accumulation of damages due to various causes and in the late 1990s these buildings had shown many deficiencies and structural weaknesses. There has been an urgent need in renovation and seismic upgrading. The feasibility study had shown that the demolition was a better option. Samples have been taken before demolition.

Diameters of core samples were of 46, 53, 75, and 100 mm. The length-to diameter ratio was approximately equal to 1, and in several cases-2. Slabs, beams and columns have been investigated. In two buildings samples were taken from the internal axes. So, concrete had been under common indoor environment of a residential building. Samples from one building were taken from both indoor and outdoor faces of columns. In order to exclude the influence of alternating bending moments in columns due to previous earthquakes , the samples were taken at columns mid-height. This also excludes the effect of different degree of compaction and segregation at the bottom and top parts of columns and a possible (15-20)% difference in properties.

Samples from beams and slabs were taken at sections of low stress intensity, at the points of theoretical contra-flexion. Samples which included cut reinforcement were not analyzed in this paper. The level of sustained stresses in columns has been assessed to be approximately of 0.27 fck. Earthquake effects could rise them up to 0.55fck. In all cases , concrete prior to testing had been subjected to a long term compressive and flexural stresses. Bridge samples have been mainly taken from the lateral diaphragms which were subjected to low stresses. Climatic conditions have drastically different from those in Nicosia. Seasonal variations of extreme temperature were from -15 deg. C to +33 deg. C, and the relative humidity did not descend below 50%. In Nicosia the monthly extreme maximums of temperature during a year are estimated to be between +20 deg.C and =41 deg. C, and the monthly extreme minimums - between +3 deg.C and +22 deg. C. The monthly mean relative humidity is changing from 20% in July (with the observed minimum of 2%) to 55% in January (with the maximum of 90%).

Samples from a building constructed during winter period had no excessive voids, honeycombing and cracks. Excess voidage was approximately 3%. But samples from buildings constructed during summer time had it much larger, namely, (13-15)%.

For the comparison, concrete samples with the same composition as that of old concrete have been prepared and tested at the age of 28-33days.

**Loading conditions**

Static testing has been conducted at a stress rate of 0.4 MPa/sec. Before testing the point of resultant load application was centered at the actual physical axis of stiffness. It was done by preliminary loading up to the stress of 0.2 fck and getting the same strains on four sides of a specimen. Since the aim of investigations was in assessment of both elastic and plastic deformations, they were separated by loading in 10 stages and keeping constant stress during ten minutes at each of these 10 stages.

Under dynamic loading the rate of stress increase varied between 1.2 MPa/sec and 234 MPa/sec. The time of dynamic loading was within the range from 0.098 sec to 18.7 sec. The rate of deformations has varied between 0.00466 mm/s and 0.846 mm/s. The main bulk of low cycle fatigue testing had the frequency of 5 Hertz, which translates into 0.1 s loading time within each full cycle of loading and reloading. The loading time under low cycle action was the same as the shortest investigated time under dynamic loading. Cyclic loading alternated between zero-stress and the specified maximum value, i.e. the asymmetry coefficient was zero. This approach allows to use experimentally determined dynamic strength as the beginning of fatigue diagram. It removes unavoidable and hard heating uncertainties associated with adoption of the starting point. This also provides for a close linking and uniform treatment of dynamic strength and cyclic fatigue limit.

## STATIC STRENGTH

### Compressive strength

The popularly held belief that concrete, like a vintage wine, is improving with time simply does not hold true. For years the static compressive strength of concrete has been used as the only quality index. All other properties were treated as derivatives from the compressive strength. The only source of strength increase with time is a long lasting process of cement hydration. Coarse grained old type cements with high $C_2S$ content had exhibited strength increase out to 50 years (Fig.1). More recent types of cement do not provide for this. Cements with larger proportion of $C_3S$ and larger specific surface area have been implemented into USA practice during the period 1926 to 1940. These changes resulted in much shorter period of strength gain and after 10 years the retrogression of it was observed, Washa [2]. In Europe similar major changes in cement characteristics occurred a bit later, but contemporary cements have 4-6 times larger surface area and approximately 4 times larger $C_3S$ / $C_2S$ ratio than cements used by M. Withey in 1910 [1]. Strength increase is dependent on a frightening number of factors and is always a conditional quantity. Not too many reliance can be placed on it. For example, BS 8110 does not permit the use of strength greater than the 28 day value , except for the elasticity modulus evaluation. No shear strength increase for concrete stronger than 40 MPa (cube strength) is allowed in this code. But in many other codes of practice the shear resistance provided by concrete is strongly linked to the static compressive strength (Fig. 2). This is a real source of mistakes while assessing capacities of old concrete. In our testing the increase was much lower than the commonly anticipated, namely (5-8)% in Nicosia and up to 18% in Lviv. The tendency is clearly visible, but definitely the strength increase is not proportional to the logarithm of age. As a vivid illustration of environmental effects, the static strength of concrete from a building constructed during the winter period in Nicosia was found to have the variation factor of 14.4% which is good even for the 28day concrete. Core tests are generally not as accurate and consistent as cube and cylinder tests, but they show exactly the same tendencies and provide the most trustful information about the actual properties of concrete in existing structures.

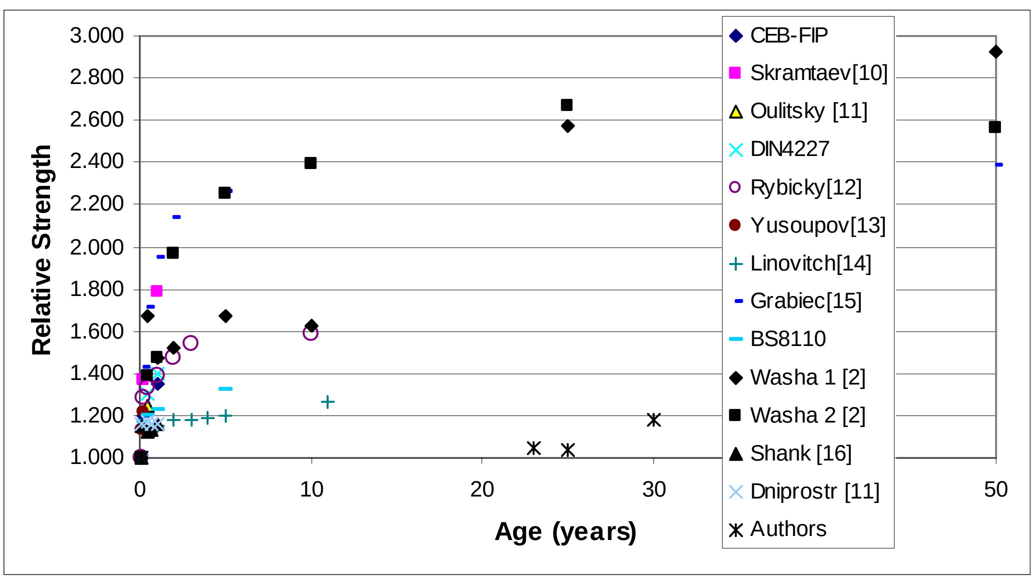


**Fig 1: Strength-Age relationship**

Our findings are visibly outside the general picture and they offset the total estimate of the strength increase. But they are not the first of this kind and, definitely, not the last. Many years ago L'Hermite had reported that after 50 years under service level loading concrete did not show an increase of strength. G. Washa and D. Fluck [17] also found that after 10.5 years of service , concrete had exhibited strength variations between 5% increase and 5% decrease. G. Washa and K. Wendt [2] observed that concrete with low $C_2S$ content and large surface area had systematically shown a decrease in strength for the period 10 to25 years.

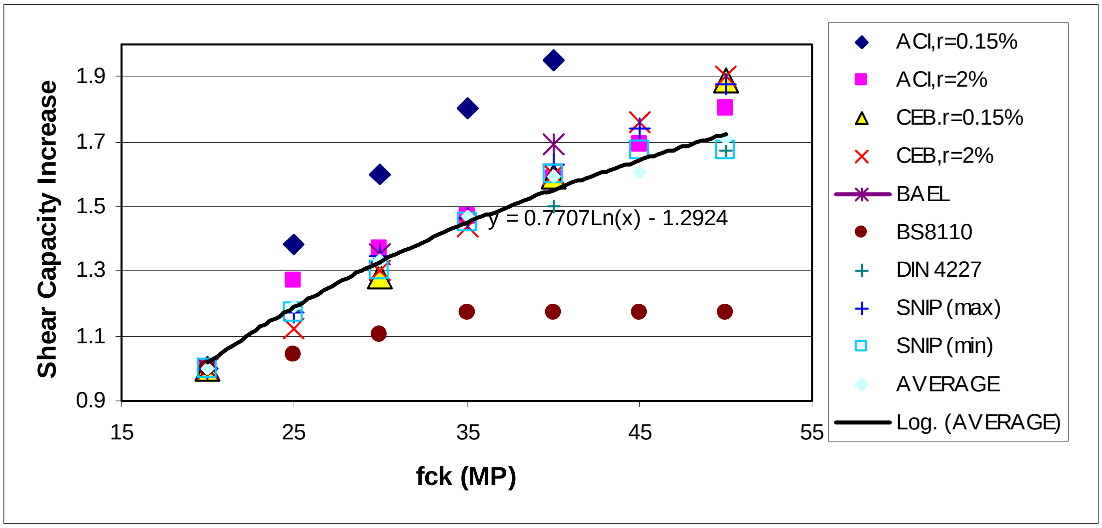


**Fig 2: Relative increase of concrete shear capacity with concrete strength**

Strength gain with age is to be considered together with the destructive processes which set up right from the time of initial setting and hardening. Depending on a factual conditions any one of these two simultaneous processes can prevail. As a rough approximation for the hot - dry conditions and a low-aggression environment the strength change of 20 year old concrete can be presented as follows:

$$K=1.1+0.34*\ln(t) - 0.15(1-e^{-0.4t}) \text{ where t is the age of concrete in years} \qquad (1)$$

The first component accounts for the strength gain and the second-for its retrogression. The multiplier of the second term restricts this effect and should be corrected for other conditions .

**Tensile strength**

One of the unfortunate characteristics of old concrete is in its low tensile strength. In several cases there have been a drop of tensile strength as compared to the value of 28 day concrete. It cannot be attributed to the increased variation only. Compressive strength increase with age is not accompanied by the proportional increase of tensile strength (Fig.3). Not only absolute value of tensile strength is affected by age but its correlation with the compressive strength is also undergoing considerable changes. Young concrete shows a definite increase of tensile strength with the increase of compressive strength, but old concrete does not follow this rule (Fig.3). The ratio between tensile and compressive strength is substantially decreasing with age of concrete (Fig.4). Old concrete results are completely out of the margins experienced in young concrete. The tensile /compressive strength ratio is much lower than that of young concrete. For the comparable compressive strength, in old concrete this ratio varied between 0.041 and 0.068 with the average value of 0.047 and in young concrete it was within the range from 0.0834 to 0.117 with the average of 0.096. For old concrete it can be safely adopted being two times smaller than in young concrete. This signals a trouble. The main structural deficiency of concrete is getting worse with time. Within the relatively narrow strength range, that was investigated, the correlation between compressive strength and tensile-to-compressive strength ratio is very weak and cannot be used for the functional relationship.

The rate of tensile strength development is much higher than that of compressive strength. G. Washa [2] found that the neat cement samples stored in water had shown little change in tensile strength from 7 days to 50 years. In other tests the maximum tensile strength was attained in 1 year and the maximum compressive strength- in 10 years and after that there was degradation of both properties. The relationship between these two characteristics is much more complicated than what is assumed in common design practice. There is no straight-forward relationship between them. All this makes no sense , when not all conditions are clearly specified. At the same time this is the best possible proof that there is no such thing as the stable properties of concrete.

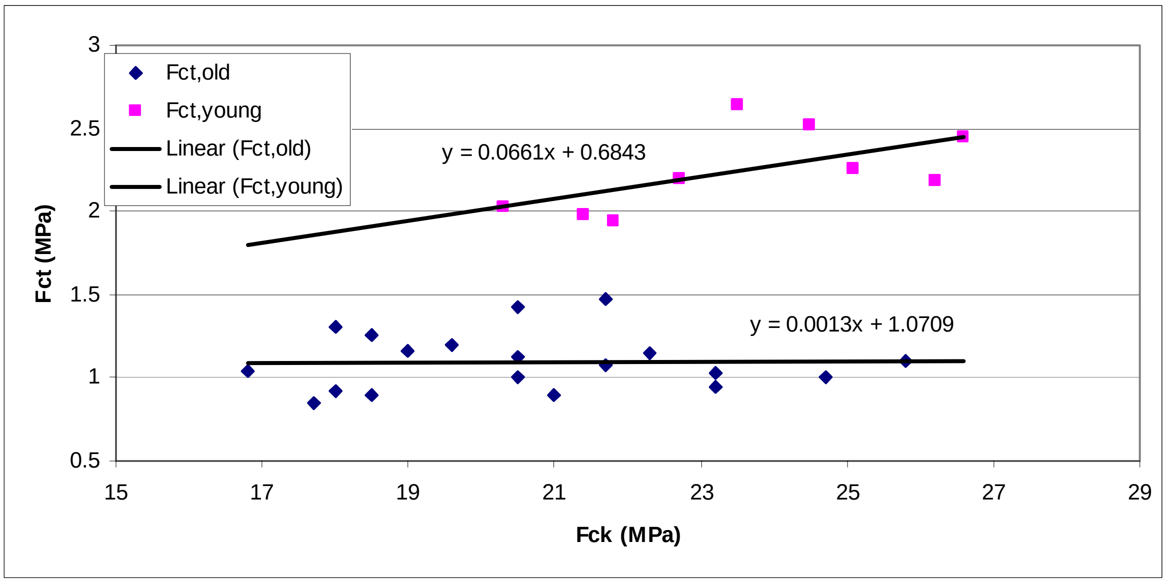


**Fig3: Tensile Compresive Strengths relationship**

One more drawback of old concrete is in a considerably large reduction of the tensile strength in elements previously subjected to a sustained compression. Since concrete is primarily is assumed to carry compressive stresses, the vast majority of existing structures are experiencing this tensile stress degradation. The reduction can be approximately of 35%. Long term service stress compression also reduces the dynamic strength and cyclic resistance.

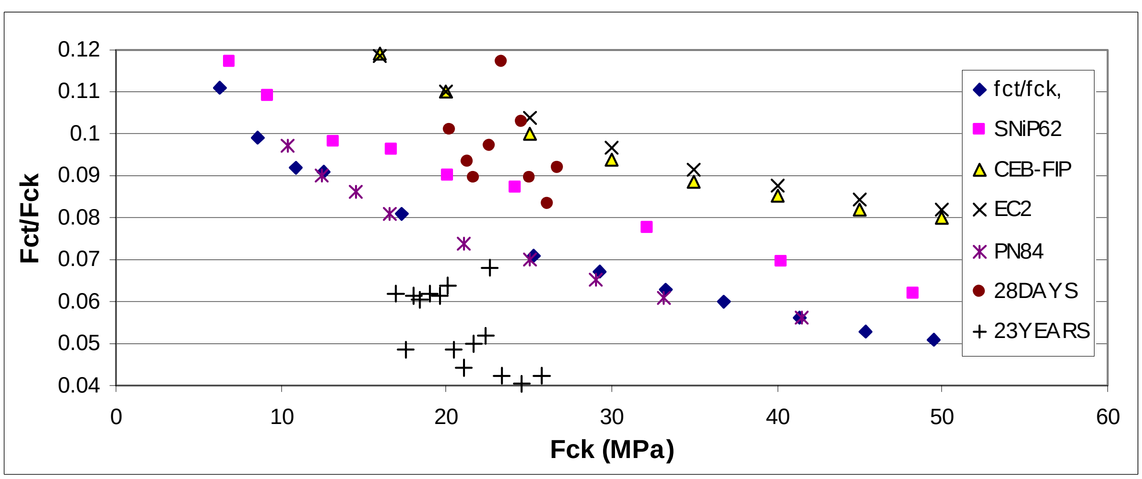


**Fig 4: Tensile Compresive Strengths Ratio vs Compressive Strengths**

The reduction of tensile strength with age and after sustained compression is adversely affecting the performance of confined concrete. Confinement is experiencing a remarkable rebirth. It was first proposed by M. Considere in 1902 [18], and developed by A. Kuryllo[19] and others, but later on the interest in it was lost. At present it is considered as the most effective method of improvement of concrete deformability. Confinement of concrete can greatly improve its performance, and according to Considere , the strains of 3% (i.e. approximately 10 times larger than unconfined concrete can accommodate) may be counted for. But if concrete loses its ability to undergo lateral tensile deformations, the effectiveness of confinement is diminishing accordingly. Confinement is useless for a material which cannot develop tensile deformations. Tests with china porcelain and gypsum had confirmed this.

In a stark contrast to the load bearing capacity evaluation in flexure, the tensile strength of concrete is used for the shearing resistance calculations. Since 1773 when C. Coulomb suggested to equate the shearing capacity to the tensile strength of concrete, these two characteristics had remained linked. Only quantitative corrections have been introduced.

Crack resistance of young concrete under cyclic loading is approximately 50% lower than that under static short term loading. Approximately the same ratio between fatigue tensile limit and static tensile strength can be adopted for the cyclic loading with alternations from zero-to-maximum. But for the old concrete both these characteristics are considerably lower, are conditional to many variables and cannot be readily assessed.

## ELASTIC MODULUS

Modulus of elasticity is increasing with age. The rate of elastic modulus increase is higher than the rate of concrete compressive strength increase. Even if there is no compressive strength increase there is always increase of the modulus of elasticity with age. All results are larger than the values recommended by codes from different countries and from values obtained on young concrete (Fig.5).

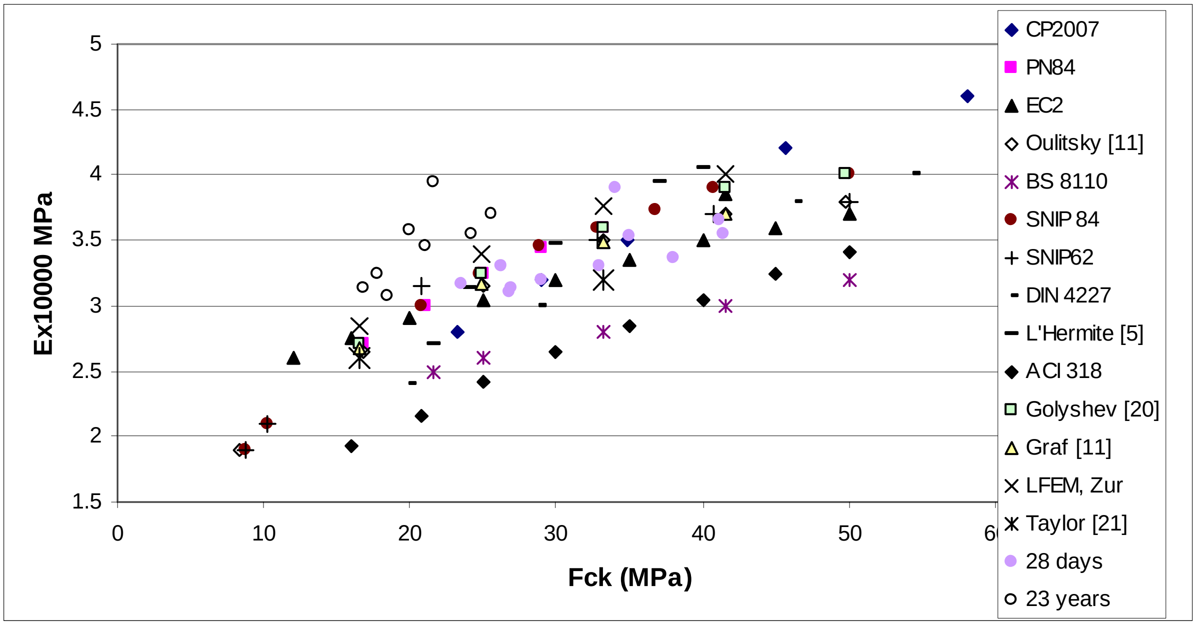


**Fig 5: Elastic Modulus vs Strength**

Modulus of elasticity of young concrete exhibits rather stable relationship with the compressive strength. Our findings for young concrete are in a good agreement with code recommendations and other experimental results. The linear fit for all data shown in Fig.5 (except old concrete results) yields the following equation with the correlation factor of 0.91:

$$Ec = (1.9 + 0.045\ fck)*10000\ MPa \quad (2)$$

The Elastic modulus of up to 25 years old concrete which was not stressed beyond the micro-cracks formation level and was not subjected to aggressive environment can be assessed as follows:

$$Ec = (0.68f_{ck} - 0.0146f^2_{ck} - 4.3)*10000\ MPa \quad (3)$$

When only the age factor is taken into consideration the elastic modulus increase of up to 25 years old concrete can be defined as:

$K_E = 1+ 0.08*Log\ (t)$, where t is the age in days. (4)

For concrete older than 25 years the increase may be assessed by the following equation:

$K_{E\ 1}= 1 + 0.07e^{log2t}$, where t is the age in years (5)

The increase of elastic modulus means the corresponding decrease of elastic component of strains. In reinforced concrete the increase of concrete modulus of elasticity results in the change of modular ratio between steel and concrete and the respective increase of stresses transferred to concrete. This phenomenon is usually overlooked. In reality the stress relaxation due to creep of concrete can be considerably reduced or nullified by the simultaneous increase due to elastic modulus change. An increase in concrete stiffness is invariably accompanied by a corresponding increase of stresses. It is of interest that cyclic loading leads to the reduction of elastic modulus. Two opposite processes are taking place. The reduction of elasticity modulus due to cyclic loading was estimated as:

$K_{E2} = 1- 0.07Log\ N$, where N is number of cycles (6)

It is very interesting, that in spite of substantial differences between contemporary concrete technology and that used by M. O. Withey in 1910, 1923 and 1937, the strength / elastic modulus ratio has remained practically within the same bracket, approximately between 800 and 1400. This confirms that common concrete is not very sensitive to some changes and with many deviations its commonly referred properties still can be acceptable.

## DEFORMATIONS

The most undesirable transformation of concrete with age is in drastic reduction of its plastic strains capacity. The stress-strain relationship of old concrete is different in every detail from that of young concrete ( Fig.6). Up to the stress level of 75% of the ultimate value it behaves as elastic material. This is happening under static loading, and under dynamic loading the range of elastic response even longer. Due to elastic modulus increase, the elastic strains of old concrete are steadily smaller than those of young concrete. The difference is increasing with age. The total strains at peak load are approximately 40% smaller than those exhibited by young concrete. Young concrete shows a rater stable relationship between strength and all components of strains (Fig.7). But old concrete within the investigated strength range practically does not have it.

Creep characteristics expressed as the ratio between plastic and elastic strains depending on the concrete strength is following the straight line relationship for both young and old concrete. For old concrete the correlation factor is 0.893 and for young-0.994. The equations for old and young concrete respectively are:

$\varphi = 1.33 - 0.027fck$ and $\varphi = 1.86 - 0.028fck$ (7)

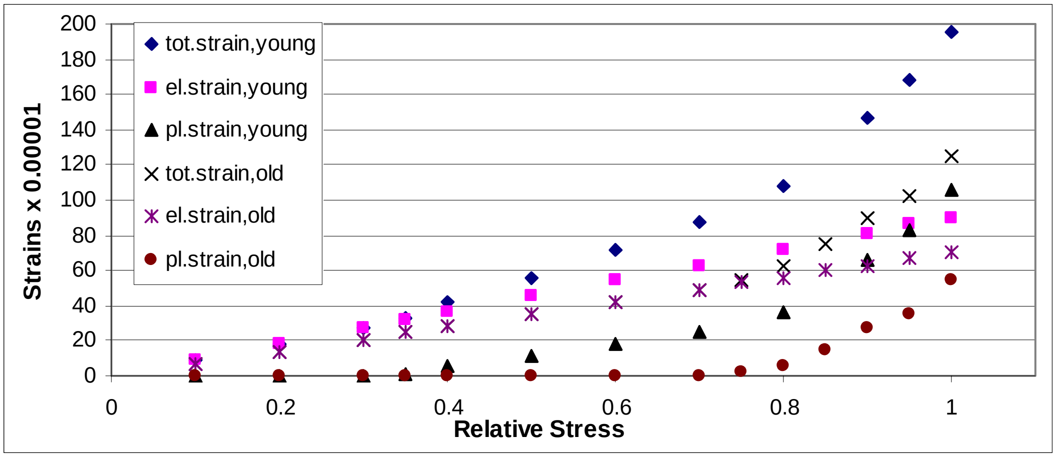


**Fig. 6: Typical Stress Strain Relationship**

The creep characteristics of young concrete depending on its strength is shown in Fig.8. Our experiments have shown considerably stronger dependence on strength than the other findings. The general tendency is in its reduction with concrete strength. Analyzing results of Oulitsky et al [22] the effect of duration of loading on the creep characteristics was found to be rather fast and can be presented by the following relationship:

$\varphi = 2.04(1-e^{-0.065t})$ (8)

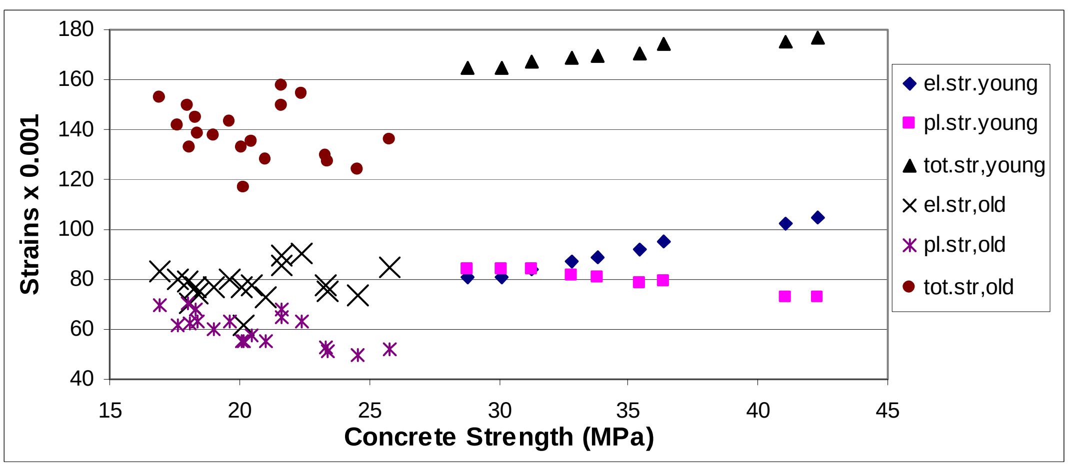


**Fig. 7: Strains vs Strength**

The ductility is equal to creep characteristics plus one. The creep factor defined as the ratio between creep strain and stress in old concrete is considerably different from that of young concrete. The ultimate creep factor of young concrete is heavily dependent on the strength (Fig 9). This relationship can be approximated by following expression:

$C = 11.55 - 0.112\ fck$ (9)

Concrete age at the beginning of loading plays a very important role. Creep strains are substantially smaller when loading commence at older age. Fig. 10 shows the creep strain as a fraction of the ultimate value depending on the age at loading. Many fold reduction of creep is to be expected when loading occur at the older age. ACI 318 and CEB-FIP methods have correction factors for the late loading age. But they do not address the constantly changing conditions of loading. The modification factor accounting for the age at loading can be adopted as follows:

$K = 0.95 - 0.002t + 1.98t^2$ , where t= age in days (10)

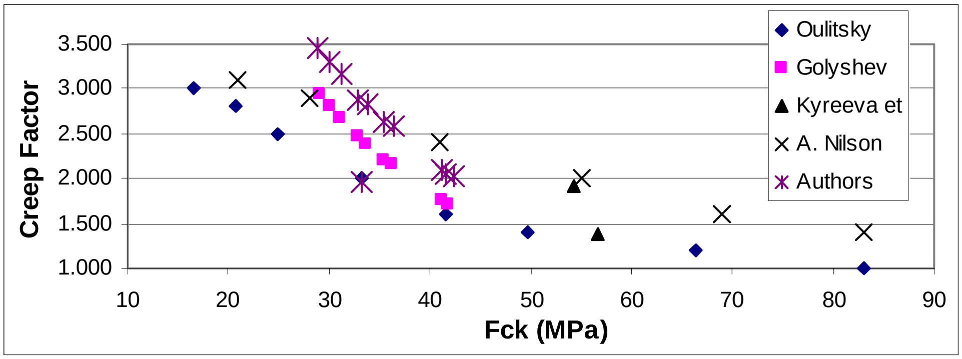


**Fig. 8: Creep characteristics vs Strength**

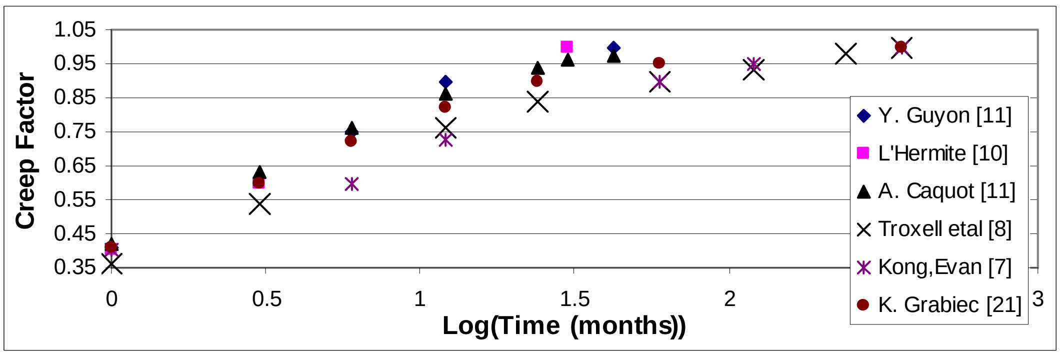


**Fig. 9: Creep Factor vs Time**

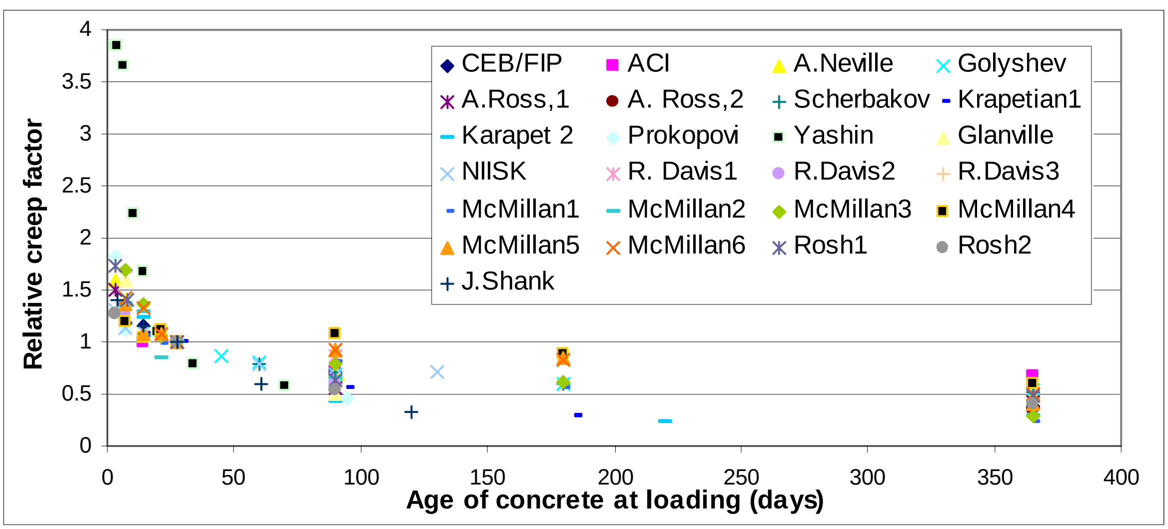


**Fig. 10: Conrete age at loading vs relative plastic strains**

Ultimate strains of old concrete are much smaller than those of young concrete. The difference is increasing with age. This is in line with the reduction of ultimate strains with concrete strength increase (Fig.11). Concrete strength increase from 10MPa to 50 MPa is accompanied by the reduction of ultimate strains from 0.0044 to 0.0024, i.e. nearly two times. Commonly adopted strains of 0.0035 are not conservative for the concrete grades higher than C25. For old concrete this value has no any justification. It can be in a gross error. In spite of the fact that the differentiation of ultimate strains depending on the concrete strength has been adopted in CEB-FIP Model Code, BAEL, Ukrainian and some other codes of practice, this principle was not followed in EC2. The fixed value is recommended for both static and seismic conditions. The effective concrete characteristics in terms of both strength and strains, as it was proposed by M. Nielsen [24], are to be used.

## DYNAMIC STRENGTHENING AND LOW-CYCLE FATIGUE

Rate of loading is an exceptionally strong factor in both dynamic and low-cycle fatigue loading. Both strength and deform-ability cannot be dissociated from the rate of loading. Old concrete exhibits very different dynamic behaviour as compared to young concrete. Dynamic properties of concrete are substantially deteriorating with time. Dynamic strengthening is continuously diminishing and can cease to exist (Fig.12). It is a real cause for alarm. Dynamic strengthening is possible only when a material has a capacity of plastic deformations. Purposely tested gypsum specimens had shown no dynamic strengthening. Concrete with age is losing its ability to develop plastic strains and becoming brittle and fragile under dynamic and seismic loading. Dynamic strengthening of young concrete was found to be many-fold larger than that of old concrete: 4 times in compression and 7 times in tension.

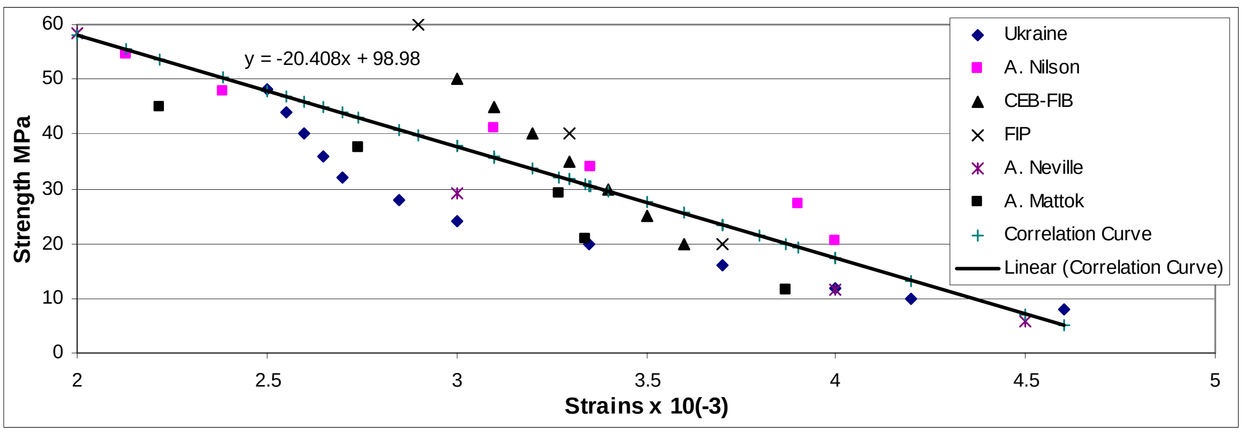


**Fig. 11: Ultimate Strains vs Concrete Strength**

When related only to the time of loading in seconds, the dynamic strengthening in compression for young and old concrete was respectively assessed as:

$$K_{d,c,y} = 1.19 - 0.04Ln(t) \text{ and } K_{d,c,o} = 1.05 - 0.09Ln(t) \quad (11)$$

Especially large difference was observed in tensile dynamic strengthening. For young and old concrete it was assessed to be accordingly:

$$K_{d,s,y} = 1.15 - 0.03Ln(t) \text{ and } K_{d,s,o} = 1.02 - 0.004Ln(t) \quad (12)$$

Dynamic strength provides the starting point for the fatigue curve. It means that for old concrete the origin of this curve is to be shifted down. Seismic capacities assessed on the basis of low cycle fatigue strength are drastically diminishing irrespective of their actual correlation with the number of loading cycles.

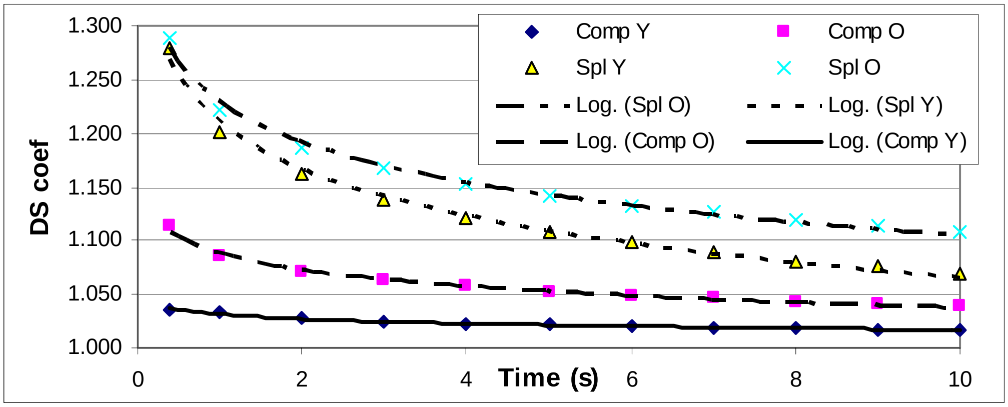


**Fig. 12: Dynamic Strengthening Depending on speed of loading**

When we are counting for 100 or 200 seismic loading cycles the strength is invariably lower than the static strength. This phenomenon was already known for some years but it is not yet accepted for the practical use. The following set of fatigue strength data related to 150 loading cycles provides a strong proof, Levtchitch [25, 26].

| Author | I. Korchinsky | H. Muguruma | K. Aas-Jakobsen | R. Tepfers and T. Kutti | V. Levtchitch |
|---|---|---|---|---|---|
| Fatigue limit | 0.80 -0.93 | 0.90 | 0.861 | 0.851 | 0.818 |

In these experiments the effect of dynamic strengthening of young concrete was estimated to be nullified by approximately 15 initial cycles of loading. So, there is no point in adopting seismic strength larger than the static one. When seismic action is treated as the low-cycle fatigue loading , just the opposite is the case: seismic strength is lower than the standard static strength.

A definite link between tensile strength and the low-cycle fatigue limit has been observed (Fig.13). The linear relationship with the correlation factor of 0.97 was found between the low-cycle fatigue strength and the tensile / compressive strength ratio. Since old concrete may have approximately two times lower tensile / compressive strength ratio, its fatigue capacity is also substantially lower.

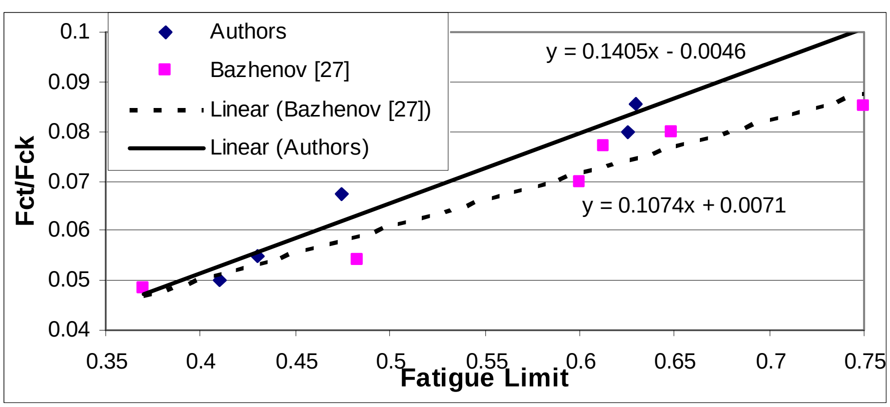


**Fig. 13: Fatigue Limit vs Static Tension/Compression Strength Ratio**

## CONCLUSIONS

Seismic capacities of concrete are degrading with age. Old concrete is continuously getting less ductile and less adaptable to seismic loading. In the course of time it transforms into increasingly brittle and seismically fragile material. The total strains at peak load can be up to 50% smaller than those recorded in young concrete. The elastic response is extended up to the tress level of 75% of the ultimate value. The ability to develop residual deformations is continuously diminishing with time and can be roughly assessed to be approximately a half of values characteristic for young concrete. This difference will definitely increase for the concrete older than the investigated 23-30 years old concrete.

Both creep characteristic and creep factor are substantially smaller than those of young concrete. The age of concrete at loading plays a very strong role in shaping the performance pattern of concrete.

Static compressive strength increase due to continuous hydration of cement should be considered with the simultaneous destructive processes. Newer types of cement with much larger specific surface area and increased content of tri-calcium silicate do not provide for a long period of compressive strength increase. As a rule 20 years old concrete does not show any considerable increase in strength. Moreover, under seismic conditions the static compressive strength is not a characteristic of prime importance. An increased compressive strength does not improve seismic performance. Seismic loading converts an increased compressive strength of old concrete into its dynamic weakness. Stiffness of old concrete is achieved at the expense of ductility which predetermines the mode of dynamic behaviour.

Dynamic strengthening of old concrete was found to be much lower than that of young concrete: 2-4 times in compression and up to 7 times in tension. Tensile-to-compressive strength ratio is approximately two times lower. In cases when there was no strength increase, there was always increase of the modulus of elasticity. A 30% increase over 20 years can be treated as a safe assumption.

Due to low tensile strength, old concrete contribution in resistance of shear cannot be relied on and accounted for. A loss of tensile deform-ability in lateral direction is badly influencing the effectiveness of confinement.

Old concrete speaks against the theory of viscous yielding of cement gel as the only physical reason of residual strains. Extensive micro- cracking results in the development of residual deformations.

Performance based analysis requires much more intelligent use of available capacities of concrete, than the force dominated methods which were used up till now. The technical basis for it is to be widely expanded. The existing data are not systematized and cannot be used for generalization. Many old experiments and idees, which did not get an appropriate attention, are to be revisited and developed.

## REFERENCES


1. Withey, M. O., "Fifty Year Compression Test of Concrete." ACI Journ. Proc. V.58, No 6,Dec.1961.
2. Washa, G. W. & Wendt, K.F., "Fifty Year Properties of Concrete". ACI Journ. Proc. Title No71-4, Jan. 1975.
3. Troxell, G.E., Raphael, J. M.,& Davis, R. E. "Long-Time Creep and Shrinkage Tests of Plain and Reinforced Concrete." Proc. ASTM, V.58, 1958.
4. Gvozdev, A. A., Yashin, A. V., "Elastic deformations and creep of concrete." Coll. Strength, Structural Changes and Deformations of Concrete. Stroiizdat, Moscow,1978.
5. L'Hermite, R., "Idees Actuelles sur la Technologie du Beton." Paris, 1955.
6. Guyon, Y., "Beton Precontraint." Paris, 1953.
7. Kong, F. K. and Evans, B.H., "Reinforced and Prestressed Concrete." Hong Kong, 1987.
8. Freyssinet, E., " Une Revolution dans les Techniques du Beton." Paris, 1936.
9. Le Camus, B., "Recherches experimentales sur la Deformation du Beton et du Beton Arme." C. R. Rech. Lab. BTP, 1945-1946.
10. Baikov, V., Sigalov, E., "Reinforced Concrete Structures." Stroiizdat, Moscow, 1985.
11. Oulitsky, I., "Determination of Creep and Shrinkage Deformations of Concrete." Gosstroiizdat, Kiev,1972.
12. Rybicky, R., "Damages and Defects of Buildings Structures." Russian translation. Moscow,1982.
13. Yousupov, Z., "Performance of Reinforced Concrete Structures under Low-Cycle Fatigue Loading in Climatic Conditions of Central Asia." Fan, Tashkent, 1988.
14. Linovich, L., "Design and Detailing of Elements of Civil Buildings." Budivelnyk, Kiev, 1972.
15. Grabiec, K., "Concrete Structures". Warsawa-Poznan, 1987.

16. Shank, J. R., " Plastic Flow of Concrete at High Overload." ACI Journ., V.20, No 6, Feb. 1949.
17. Washa, G., Fluck, D., "Effect of Sustained Loading on Compressive Strength and Modulus of Elasticity of Concrete." ACI Journ., V.46, No 9, 1950.
18. Considere, M., "Resistance a la Compression du Beton Arme et du Beton Frette." Genie Civil, T. XLII, Paris, 1902.
19. Kuryllo, A., Thullie, M., "Berechnung der Umschnuten Eisenbton Saulen." Beton und Eisen. Heft 19/20, Berlin, 1918.
20. Golyshev, A., Tkachenko, I., "Practical Methods of Accounting for Creep and Shrinkage in Analysis of Reinforcd Concrete Structures." NIISK, Kiev, 2000.
21. Taylor, J., "Testing of Materials under High Rate of Loading." Mechanics, No 10, Annotated translations and summeries of foreign periodic literature." Moscow, 1980.
22. Oulitsky, I., Kyreeva, S., Fanstil,I., "Losses of Prestress due to Creep and Shrinkage of Concrete in Reinforced Concrete Structures." NIISK, Kiev,1962.
23. Nilson, A., "Design of Prestressed Concrete." John Willey &Sons Inc, N.Y., 1979.
24. Nielsen, M., "Limit Analysis and Concrete Plasticity." CRC Press, London, N.Y, Washington, 1999.
25. Levtchitch, V., Kvasha, V., "Seismic Capacities of Old Concrete." Proc., *fib*-Symposium Concrete Structures in Seismic Regions, Athens, 2003.
26. Levtchitch, V., "Shear Fatigue and Seismic Response of Reinforced Concrete Flexural Members." The Cyprus Journal of Science and Technology. Vol.1, No 3, Nicosia, 1997.
27. Bazhenov, Y., Concrete under Dynamic Loading. Moscow, 1970.