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# The Cyclic Loading of Normal Concrete in a Specific Stress Range

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## ABSTRACT

This research presents a study about the effect of static cyclic loading at compression on the properties of normal concrete, which are: the modulus of elasticity, the compressive strength and the ultimate strain.

The static cyclic loading of concrete is achieved by loading-unloading-reloading at compression, for a short duration, in a specific stress range and for a few number of cycles.

Experimental program includes tests for sixteen concrete specimens with maximum compressive strength 30 MPa. Twelve of the specimens are tested under a static cyclic loading, at the stress range (40 to 80) percent of the maximum compressive strength. The four remaining specimens are tested under uniaxial loading till failure. The cyclic loading is carried out for a few number of cycles, which is determined with (5, 10, 15, 20) cycles.

Analytical part of this study is based on mathematical formulations for the stress-strain response, which are developed from the test results, in order to get the properties of concrete. A comparison between the properties of concrete in the two cases of loading (cyclic and uniaxial), is carried out. The results show an obvious improvement in the properties of concrete under cyclic loading, when achieved in the specific stress range (40 to 80) percent of the maximum strength, and for the number of cycles 15 or 20 cycles.

The improvement in the properties of normal concrete under cyclic loading is the fundamental for the application of this kind of loading on High-Strength concrete. Hence, the cyclic loading causes an increase in the ultimate strain of normal concrete, so it may be of greater efficacy in High-Strength concrete.

**KEYWORDS:** Cyclic loading, Unloading, Reloading, Stress–strain curve, Modulus of elasticity, Compressive strength, Ultimate strain.

## INTRODUCTION

The design of concrete structures is mainly depending on compression tests under uniaxial loading until failure occurs due to the crushing of concrete at ultimate strain. The typical shape of the stress-strain curve is closely associated with the mechanism of internal progressive microcracking, as shown in Fig. (1).

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On the other side, many of engineering structures are liable to the cyclic loading in service conditions. The cyclic loading is represented as a live load in the residential, industrial and hydraulic constructions.

Many researchers offered experimental studies about cyclic loading such as: Sinha (1964), Karasan and Jirsa (1969), Sakai and Kawashima (2000) and Bangash (2001). The results of the previous experimental researches showed that repeated loading and unloading do not influence the behavior of concrete, so long as the value of stress does not exceed about 50 percent of the strength in compression, while a substantial decrease in strength as well as in stiffness is observed whenever stress exceeds about 85% of strength.

For each cycle of unloading and reloading, a hysteresis loop is formed, and the area of this loop decreases with each successive cycle, but eventually increases before fatigue failure. The stress-strain curve for monotonic loading serves as a reasonable envelope for the peak values of stress for concrete under cyclic loading, see Fig. (2).

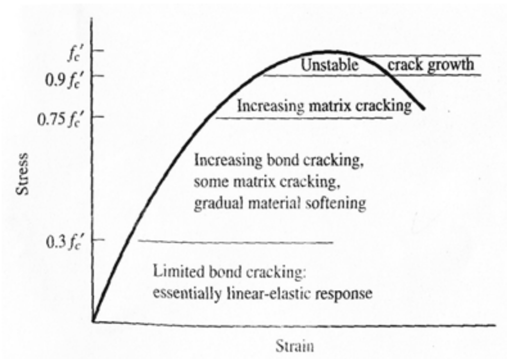


**Figure (1): A typical stress-strain curve for concrete subjected to uniaxial loading**

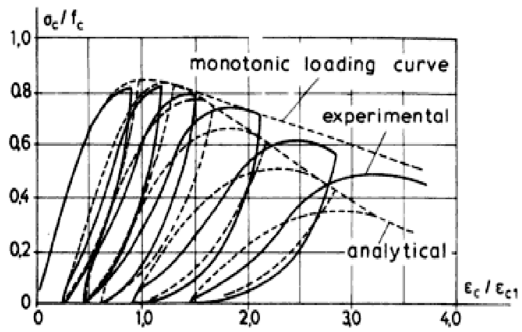


**Figure (2): Stress-strain diagram for repeated loading and complete unloading**

Among the analytical models proposed for estimating the response of concrete to cyclic loading are: Blakely and Park (1973), Al-Sulayfani, Darwin and Pecknold (1974), Sadeghi and Nouban (2010), Lokuge, Sanjayan and Setunge (2004), Aslani and Jowkarmeimandi (2012), Sakai and Kawashima (2000) which combine simplicity with a reasonably accurate description of the basic characteristics of the actual behavior of concrete.

Most of previous studies were performed to decide fatigue limit of concrete at large number of cycles, predict unloading and reloading paths or to develop analytical models which simulate behavior of concrete under cyclic loading.

In this research, the aim is to evaluate the behavior of normal concrete under a static cyclic loading for a few number of cycles, in a specific range of stress, whereas the repeated loads will cause changes in the internal construction of concrete. These changes may create a good influence on the properties of concrete.

## EXPERIMENTAL PROGRAM

A mixture of concrete with maximum compressive strength $f_C'$ = 30 MPa is designed. Water-to-cement ratio of concrete is 0.5. The maximum size of aggregate is 14 mm. The maximum diameter of sand is 0.5 mm.

The strain in concrete is measured by using Teclock Dial Indicator, Model TM-110, Graduation 0.01 mm. The strain gauges glued at two sides of the specimen.

Sixteen prism specimens with a cross-section of (100×100) mm and a height of 400 mm are tested. Twelve of these specimens are subjected to static compression cyclic loading, when the stress range is between 40 and 80 percent of the maximum compressive strength. The four remaining concrete specimens are tested under uniaxial loading from zero till failure.

The cyclic loading is achieved by loading-unloading-reloading for a few number of cycles, which is determined with (5, 10, 15, 20) cycles.

Experimental program is shown in Table (1).

## EXPERIMENTAL RESULTS

According to Table (1), twelve specimens are tested under cyclic loading and the experimental stress-strain curve is drawn for every specimen.

For instance, the test for specimen (1) under cyclic loading will be detailed.

**Table 1. Experimental program for concrete specimens**

| Type of loading | Number of specimen | Number of cycles | Range of stress |
|---|---|---|---|
| Cyclic loading | 1, 2, 3 | 5 | $(0.4\ f'_C)$ to $(0.8\ f'_C)$ = (12) to (24) MPa |
| | 4, 5, 6 | 10 | |
| | 7, 8, 9 | 15 | |
| | 10, 11, 12 | 20 | |
| Uniaxial loading | 13, 14, 15, 16 | . | From zero till failure |

Specimen (1) is subjected to cyclic loading for five cycles, in the range of stress (12-24) MPa. The test for specimen (1) is carried out as follows:

First, specimen (1) is loaded continuously from zero to ($12\times10^4$) N. Then, the specimen is subjected to cyclic loading for five times, in the range of load from ($12\times10^4$) N to ($24\times10^4$) N. After that, a continuous loading is applied till failure**.**

The load is applied with a constant intensity, and at every value of load the strain is measured by two strain gauges, placed on opposite sides of the specimen.

The experimental results due to cyclic loading for specimen (1) are shown in Table (2).

**Table 2. The experimental results for specimen (1)**

| **Specimen (1) subjected to cyclic loading for five cycles in the range of stress (12-24) MPa** | | | |
|---|---|---|---|
| **The load** $\times10^4$ (N) | **The stress** (N/mm$^2$) | **The strain** ($\times10^{-3}$) | **Steps of loading** |
| 0 | 0 | **0** | Loading |
| 4 | 4 | **0.145** | |
| 8 | 8 | **0.235** | |
| 12 | 12 | **0.313** | |
| 15 | 15 | **0.415** | First cycle (loading-unloading) |
| 18 | 18 | **0.513** | |
| 21 | 21 | **0.640** | |
| 24 | 24 | **0.850** | |
| 21 | 21 | 0.760 | |
| 18 | 18 | 0.678 | |
| 15 | 15 | 0.608 | |
| 12 | 12 | 0.505 | |
| 15 | 15 | **0.570** | Second cycle (reloading-unloading) |
| 18 | 18 | **0.663** | |
| 21 | 21 | **0.755** | |
| 24 | 24 | **0.870** | |
| 21 | 21 | 0.813 | |
| 18 | 18 | 0.725 | |
| 15 | 15 | 0.638 | |
| 12 | 12 | 0.533 | |
| 15 | 15 | **0.590** | Third cycle (reloading-unloading) |
| 18 | 18 | **0.685** | |
| 21 | 21 | **0.783** | |
| 24 | 24 | **0.880** | |
| 21 | 21 | 0.838 | |
| 18 | 18 | 0.725 | |
| 15 | 15 | 0.640 | |
| 12 | 12 | 0.538 | |

| | | | |
|---|---|---|---|
| 15 | 15 | **0.598** | Fourth cycle (reloading-unloading) |
| 18 | 18 | **0.695** | |
| 21 | 21 | **0.790** | |
| 24 | 24 | **0.888** | |
| 21 | 21 | 0.845 | |
| 18 | 18 | 0.733 | |
| 15 | 15 | 0.653 | |
| 12 | 12 | 0.553 | |
| 15 | 15 | **0.608** | Fifth cycle (reloading-unloading) |
| 18 | 18 | **0.700** | |
| 21 | 21 | **0.798** | |
| 24 | 24 | **0.898** | |
| 21 | 21 | 0.845 | |
| 18 | 18 | 0.738 | |
| 15 | 15 | 0.653 | |
| 12 | 12 | 0.568 | |
| 15 | 15 | **0.635** | Loading till failure |
| 18 | 18 | **0.700** | |
| 21 | 21 | **0.805** | |
| 24 | 24 | **0.898** | |
| 27 | 27 | **1.000** | |
| 30 | 30 | **1.150** | |
| 33 | 33 | **1.363** | |
| 36 | 36 | **1.555** | |

The stress-strain curve for specimen (1) is drawn in Fig. (3), depending on experimental results from Table (2).

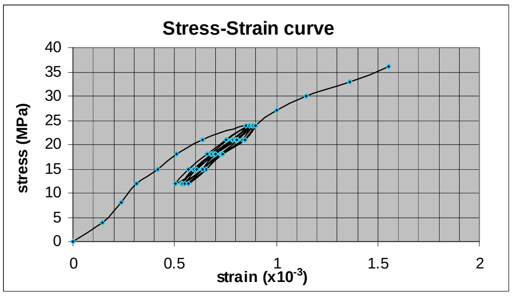


**Figure (3): Experimental curve for specimen (1) under cyclic loading, for five cycles**

The cyclic loading stage for specimen (1) is clarified by using large scale in Fig. (4).

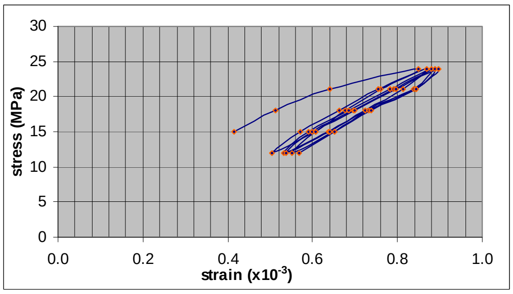


**Figure (4): Cyclic loading stage for specimen (1)**

The stress-strain curves for the other specimens, which are subjected to cyclic loading, are drawn with a resembling way. The curves are shown in the following Figures.

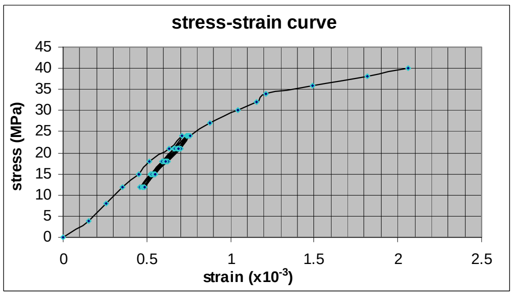


**Figure (5): Experimental curve for specimen (2) under cyclic loading, for five cycles**

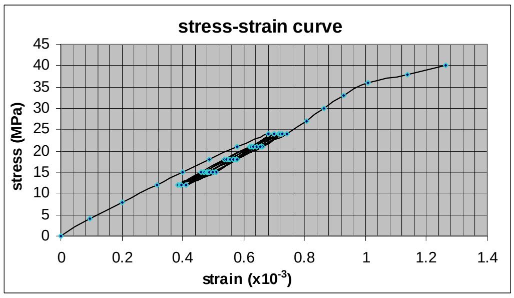


**Figure (6):Experimental curve for specimen (3) under cyclic loading, for five cycles**

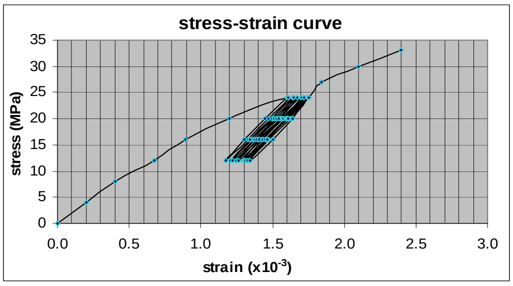


**Figure (7):Experimental curve for specimen (4) under cyclic loading, for ten cycles**

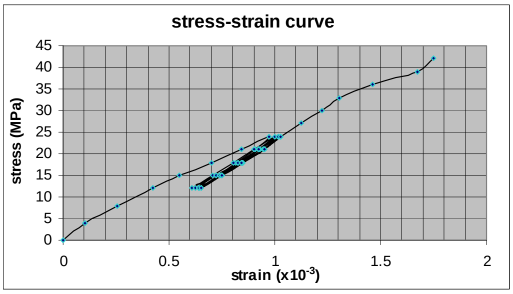


**Figure (8):Experimental curve for specimen (5) under cyclic loading, for ten cycles**

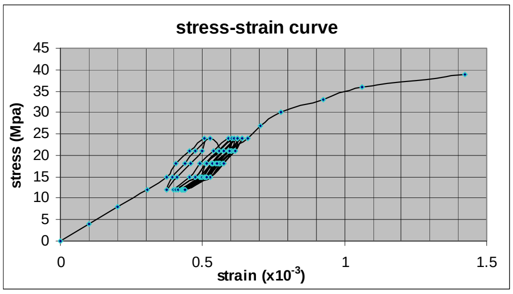


**Figure (9):Experimental curve for specimen (6) under cyclic loading, for ten cycles**

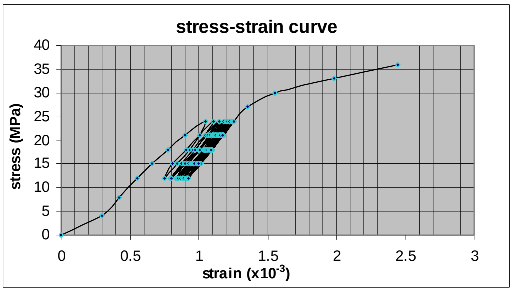


**Figure (10):Experimental curve for specimen (7) under cyclic loading, for fifteen cycles**

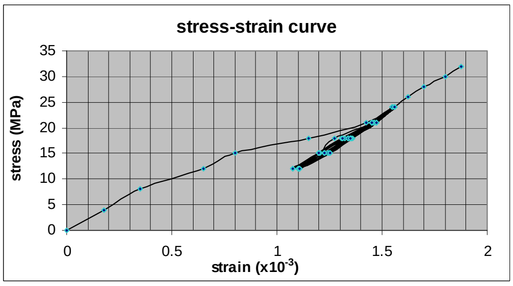


**Figure (11): Experimental curve for specimen (8) under cyclic loading, for fifteen cycles**

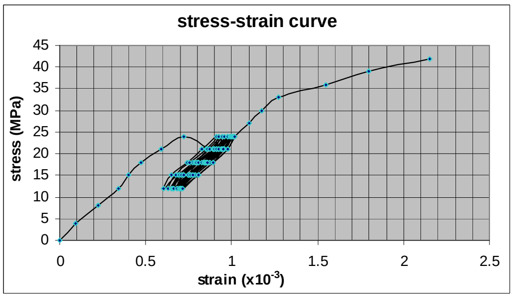


**Figure (12): Experimental curve for specimen (9) under cyclic loading, for fifteen cycles**

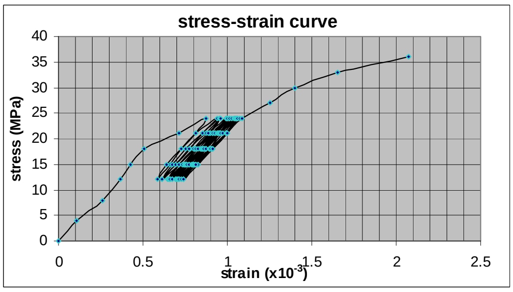


**Figure (13): Experimental curve for specimen (10) under cyclic loading, for twenty cycles**

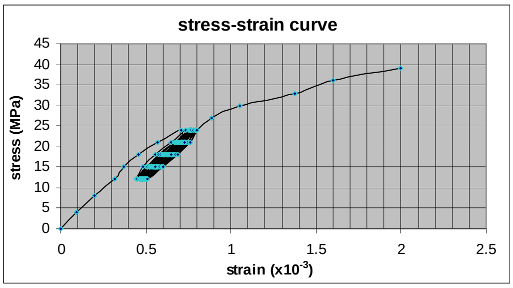


**Figure (14): Experimental curve for specimen (11) under cyclic loading, for twenty cycles**

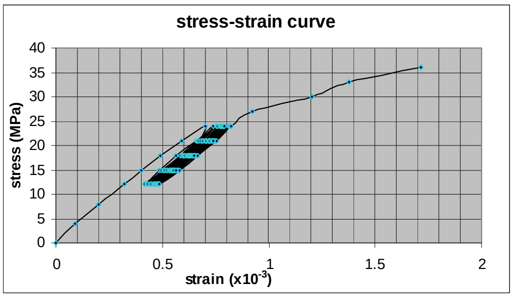


**Figure (15): Experimental curve for specimen (12) under cyclic loading, for twenty cycles**

The four remaining specimens are tested under cyclic loading and the experimental stress-strain curve is drawn for every specimen. The curves are shown in Figures (16), (17), (18) and (19), respectively.

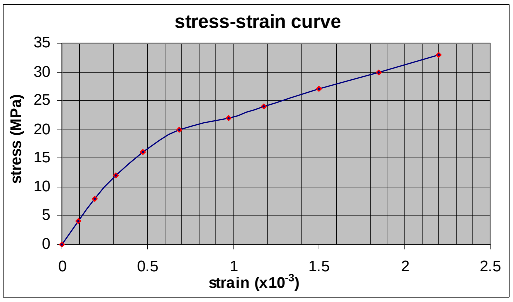


**Figure (16): Experimental curve for specimen (13) under uniaxial loading**

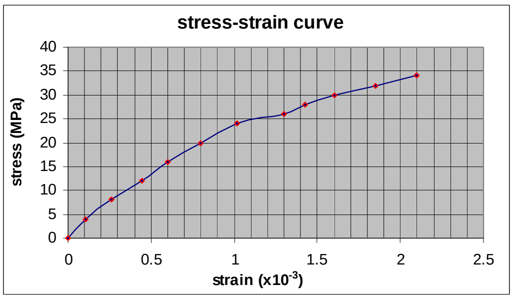


**Figure (17): Experimental curve for specimen (14) under uniaxial loading**

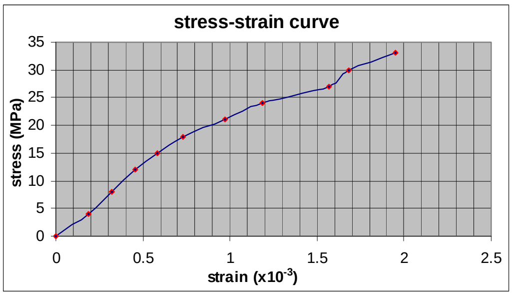


**Figure (18): Experimental curve for specimen (15) under uniaxial loading**

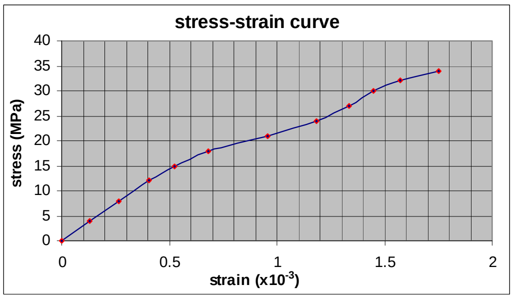


**Figure (19): Experimental curve for specimen (16) under uniaxial loading**

## ANALYSIS OF EXPERIMENTAL RESULTS

In the case of cyclic loading, the stress-strain curves for tested concrete specimens have been charted. Mathematical equations are extracted from the test results by using the method of least squares in Excel. The properties of concrete are determined from the mathematical equations as follows:

- The secant modulus of elasticity: It is drawn by using linear equation according with experimental results.
- The tangential modulus of elasticity: It is the slope of a tangent to the curve at the end of the cyclic loading stage. It is drawn by using linear equation according to experimental results.
- The compressive strength and the ultimate strain: They are the strength and strain at the peak of stress–strain curve. They are obtained by replacing

the experimental points with a parabolic equation.

For example, the properties of concrete for specimen (1) are extracted from mathematical equations, which are shown in Figures (20,A), (20,B) and (20,C), respectively.

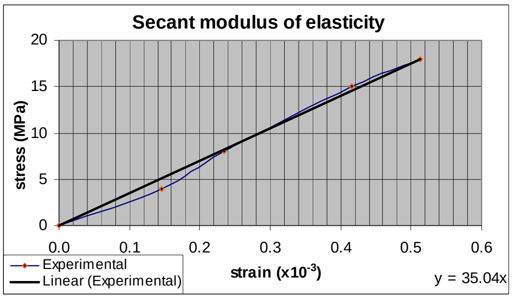


**Figure (20,A): Secant modulus of elasticity for specimen (1)**

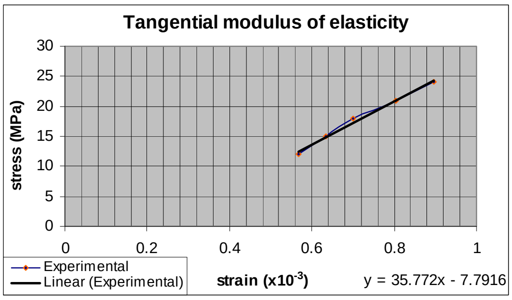


**Figure (20,B): Tangential modulus of elasticity for specimen (1)**

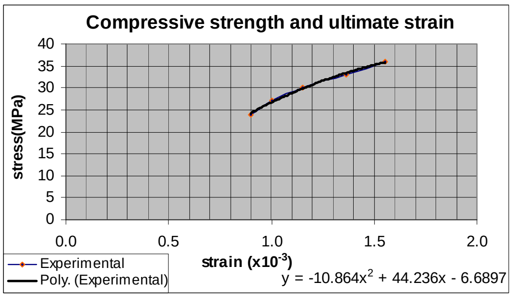


**Figure (20,C): Compressive strength and ultimate strain for specimen (1)**

The properties of concrete for specimen (1) are:

**1- The secant modulus of elasticity:**

According to Fig. (20,A), the linear equation which represents secant modulus of elasticity is:

$y = 35.04x$

x, y: The values of strain and stress at any point of line.

The secant modulus of elasticity is:

$E_C = dy/dx = 35.04$

**2- The tangential modulus of elasticity:**

According to Fig. (20,B), the linear equation which represents tangential modulus of elasticity is:

$y = 35.77x - 7.79$

The tangential modulus of elasticity is:

$E_{C1} = dy/dx = 35.77$

**3-The compressive strength and ultimate strain:**

According to Fig. (20,C), the parabolic equation which represents the compressive strength and the ultimate strain at the peak of curve is:

$y = -10.864x^2 + 44.236x - 6.6897$

$dy/dx = -21.72x + 44.23$

$dy/dx = 0 \Rightarrow x = 2.035$

$y = 38.34$

The compressive strength for specimen (1):

$y = \sigma_{C1} = 38.34$ MPa

The ultimate strain for specimen (1):

$x = \varepsilon_{C1} = 2.035 \times 10^{-3}$

The mathematical equations for the remaining specimens, which are subjected to cyclic loading, are extracted with a resembling way which is discussed above.

The mathematical equations for the twelve specimens under cyclic loading are clarified in Table (3).

In the case of uniaxial loading, the stress-strain curves for tested concrete specimens have been charted. Parabolic equations for the stress-strain response are modeled from the test results by using Excel spreadsheet, as shown in Figures (21), (22), (23) and (24), respectively.

**Table 3. Mathematical analysis for specimens under cyclic loading**

| Number of specimen | Equations of secant modulus | Equations of tangential modulus | Equations of compressive strength and ultimate strain |
|---|---|---|---|
| 1 | $y = 35.04x$ | $y = 35.77x - 7.79$ | $y = -10.86x^2 + 44.23x - 6.68$ |
| 2 | $y = 33.42x$ | $y = 43.41x - 8.89$ | $y = -8.67x^2 + 36.09x + 1.89$ |
| 3 | $y = 37.37x$ | $y = 37.01x - 3.33$ | $y = -51.35x^2 + 133.51x - 46.88$ |
| 4 | $y = 17.44x$ | $y = 29.03x - 26.67$ | $y = -12.78x^2 + 66.12x - 52.16$ |
| 5 | $y = 28.07x$ | $y = 32.40x - 9.15$ | $y = -13.41x^2 + 60.96x - 24.39$ |
| 6 | $y = 39.57x$ | $y = 56.87x - 13.39$ | $y = -27.63x^2 + 75.99x - 13.26$ |
| 7 | $y = 22.90x$ | $y = 36.32x - 21.53$ | $y = -6.54x^2 + 33.43x - 6.85$ |
| 8 | $y = 18.75x$ | $y = 26.38x - 17.30$ | $y = -13.17x^2 + 70x - 53.06$ |
| 9 | $y = 35.40x$ | $y = 38.06x - 14.88$ | $y = -9.30x^2 + 43.33x - 8.41$ |
| 10 | $y = 30.43x$ | $y = 34.01x - 12.91$ | $y = -9.40x^2 + 41.89x - 10.44$ |
| 11 | $y = 38.56x$ | $y = 39.84x - 7.80$ | $y = -5.85x^2 + 28.09x + 6.11$ |
| 12 | $y = 35.79x$ | $y = 35.27x - 4.98$ | $y = -5.91x^2 + 27.96x + 5.46$ |

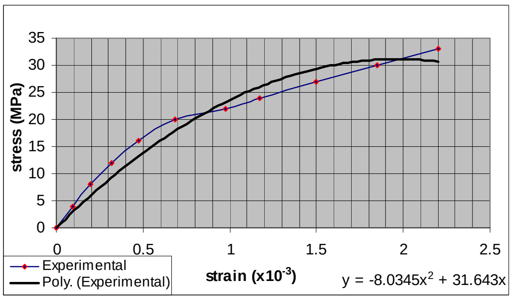


**Figure (21): Experimental and analytical curves for specimen (13), under uniaxial loading**

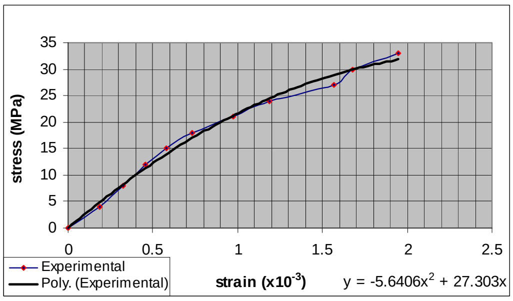


**Figure (23): Experimental and analytical curves for specimen (15), under uniaxial loading**

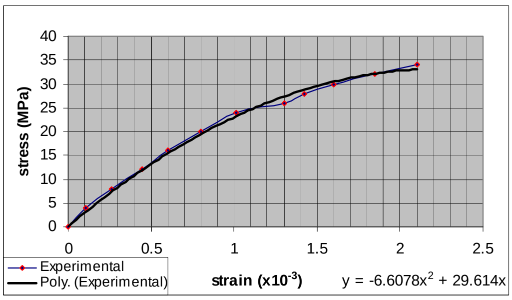


**Figure (22): Experimental and analytical curves for specimen (14), under uniaxial loading**

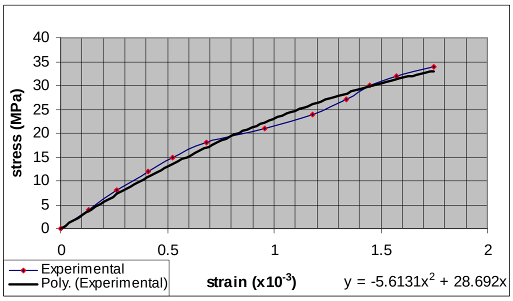


**Figure (24): Experimental and analytical curves for specimen (16), under uniaxial loading**

The parabolic equations for the four specimens under uniaxial loading are clarified in Table (4).

**Table 4. Mathematical analysis for specimens under uniaxial loading**

| Number of specimen | Equations of compressive strength and ultimate strain |
|---|---|
| 13 | $y = -8.03x^2 + 31.64x$ |
| 14 | $y = -6.60x^2 + 29.61x$ |
| 15 | $y = -5.64x^2 + 27.30x$ |
| 16 | $y = -5.61x^2 + 28.69x$ |

For example, the compressive strength and ultimate strain for specimen (13) are derived from the equation:

$$y = -8.03x^2 + 31.64x$$

$$dy/dx = -16.06x + 31.64$$

$$dy/dx = 0 \Rightarrow x = 1.969$$

$$y = 31.16$$

The compressive strength for specimen (13):

$$y = \sigma_C = 31.16 \text{ MPa}$$

The value of ultimate strain for specimen (13):

$$x = \varepsilon_C = 1.969 \times 10^{-3}$$

## RESULTS

According to the mathematical equations in Table (3) and Table (4), the properties of concrete in the two cases of loading (cyclic and uniaxial) are extracted and shown in Table (5) and Table (6), respectively.

**Table 5. The properties of concrete under cyclic loading**

| Range of stress | Number of specimen | Number of cycles | Secant modulus of elasticity $(E_C)$ | Tangential modulus of elasticity $(E_{C1})$ | Compressive strength $(\sigma_{C1})$ (MPa) | Ultimate strain $(\varepsilon_{C1})$ ($10^{-3}$) |
|---|---|---|---|---|---|---|
| (12) to (24) MPa | 1 | 5 | 35.04 | 35.77 | 38.34 | 2.035 |
| | 2 | 5 | 33.42 | 43.41 | 39.45 | 2.081 |
| | 3 | 5 | 37.37 | 37.01 | 39.89 | 1.299 |
| | 4 | 10 | 17.44 | 29.03 | 33.37 | 2.586 |
| | 5 | 10 | 28.07 | 32.40 | 44.87 | 2.272 |
| | 6 | 10 | 39.57 | 56.87 | 38.98 | 1.375 |
| | 7 | 15 | 22.90 | 36.32 | 35.84 | 2.554 |
| | 8 | 15 | 18.75 | 26.38 | 39.93 | 2.656 |
| | 9 | 15 | 35.40 | 38.06 | 42.06 | 2.329 |
| | 10 | 20 | 30.43 | 34.01 | 36.21 | 2.227 |
| | 11 | 20 | 38.56 | 39.85 | 39.79 | 2.397 |
| | 12 | 20 | 35.79 | 35.27 | 38.52 | 2.364 |

**Table 6. The properties of concrete under uniaxial loading**

| Range of stress | Number of specimen | Compressive strength $(\sigma_C)$ (MPa) | Ultimate strain $(\varepsilon_C)$ $(10^{-3})$ |
|---|---|---|---|
| From zero till failure | 13 | 31.16 | 1.969 |
| | 14 | 33.18 | 2.240 |
| | 15 | 33.04 | 2.420 |
| | 16 | 36.67 | 2.555 |
| average | . | 33.51 | 2.296 |

## DISCUSSION OF RESULTS

According to Tables (5) and Table (6), a comparison between the two cases of loading (cyclic and uniaxial) is carried out, and the following results can be drawn:

1. The tangential modulus of elasticity increased with a percentage which varies between (3) percent and (40) percent, in comparison with the secant modulus of elasticity. This increase appeared at (5,10,15,20) cycles.
2. The compressive strength after cyclic loading increased with a percentage which varies between (7) percent and (25) percent, in comparison with the average of stress in the case of uniaxial loading. This increase appeared at (5,10,15,20) cycles.
3. The ultimate strain after cyclic loading increased with a percentage which varies between (3) percent and (13) percent, in comparison with the average of strain in the case of uniaxial loading, especially when the cycles are 15 or 20.
4. In the case of cyclic loading, the increase of ultimate strain is associated with the increase of the compressive strength at the peak of stress–strain curve.
5. The increase in the values of properties of concrete in the case of cyclic loading confirms that cyclic loading has a positive influence on the properties of concrete.

For example, the stress-strain curves for specimens (7) and (11), which were subjected to cyclic loading have been charted and compared with the stress-strain curves for specimens (14) and (15), which were subjected to uniaxial loading till failure, as shown in Fig. (25).

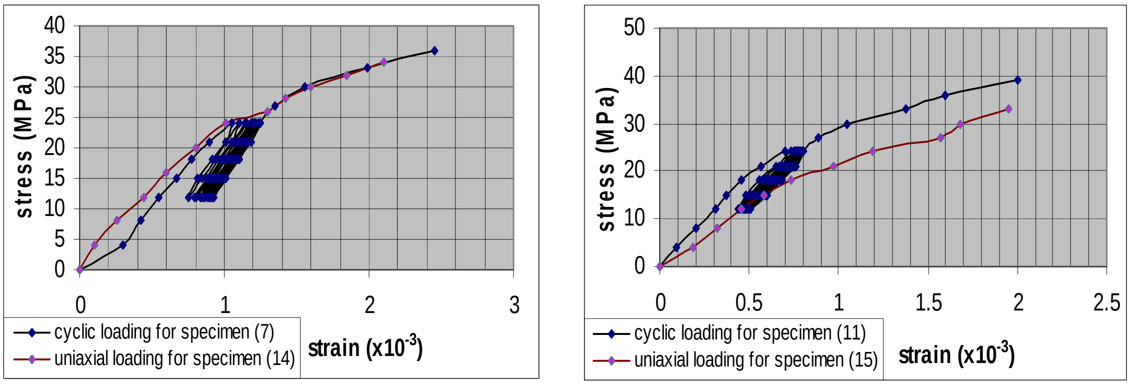


**Figure (25): Comparison between cyclic and uniaxial loading**

## CONCLUSIONS

1. The cyclic loading of normal concrete in the specific stress range (40-80) percent of the maximum strength showed an obvious improvement in the properties of concrete, in comparison with the case of uniaxial loading.
2. The application of cyclic loading for a few number of cycles produced a good effect on the properties of normal concrete, especially at fifteen or twenty cycles.
3. The increase of ultimate strain of normal concrete under cyclic loading is a noteworthy matter, due to the fact that it enables to apply this kind of loading on High-Strength concrete, which is known for its brittle falling at small values of strain.
4. The improvement in the properties of normal concrete under cyclic loading is the base to investigate the capability of cyclic loading for high strength concrete.

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