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# EVALUATION OF ENERGY DISSIPATION IN FLEXURE FOR TWO STAGE CONCRETE

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**Abstract:** Concrete is a multiphase material and the energy dissipation in concrete is considered as the index to measure the capability of its ingredients to resist cyclic loading during its service life. This paper presents the results from an investigation conducted on the behaviour of two stage concrete (TSC) subjected to constant and gradual cyclic loading. A total of 128 samples were cast and tested at 28 days of normal curing, using mixes having water/cement ratio (w/c) of 0.55, 0.65, 0.75 and 0.80 and sand/cement ratio (s/c) of 1, 1.25, 1.5 and 2.0. Empirical approach namely ratio of energy dissipation (Rn) has been used to assess the results. In general, the results are comparable either in constant or gradual cyclic loading system regardless of the variation in w/c and s/c. It seems, however, that the rate of energy dissipation was slightly higher in the samples subjected to gradual cyclic loading.

**Keywords:** *Two-stage concrete, energy dissipation, flexural cyclic loading, hysteresis loop.*

## 1.0 Introduction

In the last decades a lot of non-conventional concrete types have been developed as a new class of cement based materials with considerable improvement in their durability, mechanical and physical properties. For example, two-stage concrete (TSC), also known as preplaced aggregate concrete (PAC) is one of those non-conventional concrete which are produced and got involved in construction industry. Unlike conventional concrete, this concrete is made by first placing coarse aggregate in the formwork and then injecting a cement grout to fill the voids between the coarse aggregate particles. Mechanical properties of two-stage concrete are thus influenced by the properties of the coarse aggregate (Chen and Chung, 2013; Abdelgader and Górski, 2003), the properties of the grout and the effectiveness of the grouting process (Abdelgader, 1996; Abdelgader and Elgalhud, 2008). Mechanically TSC acts in a fundamentally different way under external stress to traditional concrete where the concrete matrix absorbs, distributes and resists the stresses. Due to the point-to-point contact between aggregate particles all the stress is passed first through the stone skeleton then, after deformation of the stone particles, restrains the aggregate and transfers the loads, as shown in Figure 1.

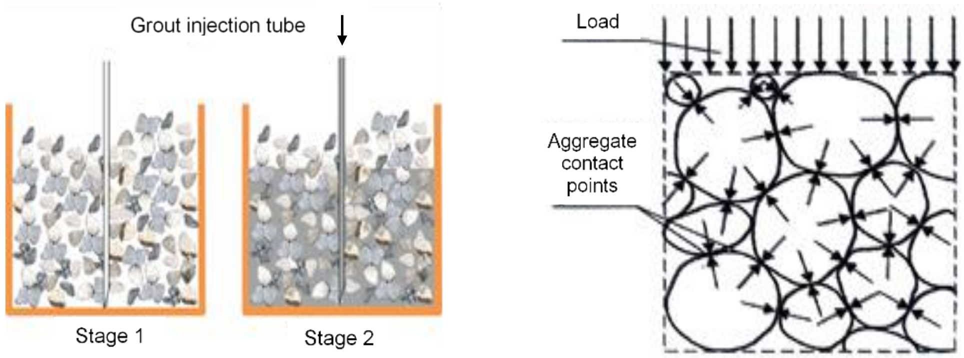



Figure 1: Manufacture of TSC and transfer of load.

Basic mechanical properties of TSC such as compressive, tensile and flexural strength have been well documented in the history of the previous research works (Tang, 1977; Awal, 1988), while there remains little or rare published data on the behaviour of TSC under periodic or alternating loading. The energy dissipation in concrete is considered as the index to measure the capability of its ingredients to resist cyclic loading during its service life. Basically, three famous empirical approaches are used to measure the energy dissipation as shown in Figure 2. The first method measures the ratio of energy dissipated per cycle to the total input energy which is denoted by (Rn). The second method quantifies the ratio of the area of each cycle to the area of first cycle and is denoted by (An). The third, also known as direct method, is the measure of the area enclosed by loading-unloading loop, which is denoted by (En) (Chen and Chung, 2013).

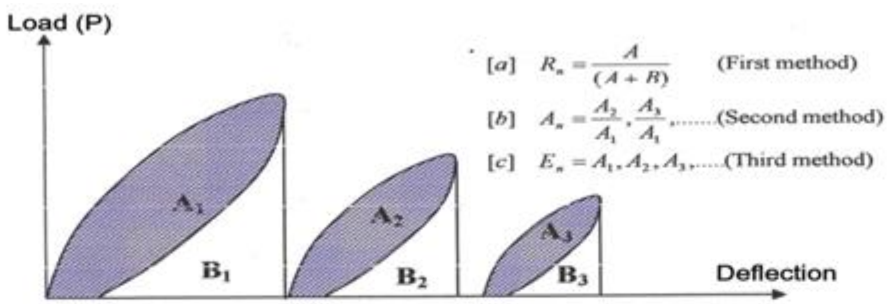



Figure 2: Empirical approaches to measure the energy dissipation.

This paper presents the results obtained from a comprehensive investigation conducted to study the behaviour of TSC subjected to either constant (sustained) or gradual cyclic loading, using standard beams loaded statically by symmetrical two-point loading as shown in Figure 3. The energy dissipation in terms of energy dissipation ratio (Rn) and other main mechanical properties are presented and discussed.

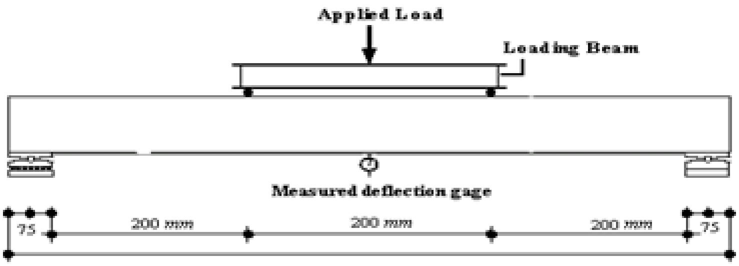



Figure 3: Test setup for flexural strength.

## 2.0 Materials and Methods

### *2.1 Materials*

Throughout this research the cement (C) used was an ordinary Portland cement. It has a 28-day compressive strength of 33.35 MPa, fineness of 3497 cm2/g, standard consistency of 24.2%, and both initial and final setting time of 2 and 4 hours respectively. All these properties were investigated according to ASTM standards (ASTM-C150, 1994). Two angular aggregates of maximum sizes 20 and 37.4 mm were used and blended with a ratio of 2:1. Tests were carried out to check the coarse aggregate suitability according to ASTM standards (ASTM C33, 1997). These tests indicated that the coarse aggregate has the specific gravity of 2.65, absorption of 1.66%, unit weigh of 1685 $Kg/m^3$ , and both crushing value and impact value of 18.85% and 21.26 % respectively. The fine aggregate (S) that was used in the grout mixture was natural beach sand having a maximum size not exceeding 2 mm with fineness modulus of 1.4. The absorption of the sand was 0.14%, and the specific gravity measured was 2.62. The grading curves of the blended aggregates and sand are illustrated in Figure 4. Quality control tests were also conducted to check its properties according to the ASTM standards (ASTM C33, 1997). Water (W) used was a fresh, dirt-free water, with a percentage of total dissolved salts not exceeding 2,000 particles per million as specified by British standards (BS-3148, 1985).

## *2.2 Concrete Mix Proportions*

Based on a previous preliminary investigations conducted by the authors and others (Abdelgader and Elgalhud, 2008; Abdurrahman, 2007) to design suitable TSC mixes using local materials, sixteen mixes were designed and implemented having w/c ratio of: 0.55, 0.65, 0.75 and 0.8 ; s/c ratio of : 1.0, 1.25,1.5 and 2.0. The absolute volume method was used to design the concrete mixes using an average volume of voids in the aggregate skeleton as 45%. Table 1 presents the contents of all the mixes investigated. One hundred and twenty-eight standard beam specimens (150mmx150mmx750mm) were cast at the rate of four samples per mix. Half of the samples (64 samples) were tested for energy dissipation in flexure under constant cyclic loading while the other half tested under gradual cyclic loading. Both flow cone and flow table tests were conducted to characterize the grout for fluidity and propagation ability.

Table 1: Grout mix proportions (Kg/m$^3$)

| w/c | 0.55 | | | | 0.65 | | | | 0.75 | | | | 0.80 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| s/c | 1 | 1.25 | 1.5 | 2 | 1 | 1.25 | 1.5 | 2 | 1 | 1.25 | 1.5 | 2 | 1 | 1.25 | 1.5 | 2 |
| C | 360 | 334 | 312 | 275 | 333 | 311 | 292 | 259 | 310 | 291 | 274 | 245 | 300 | 282 | 266 | 239 |
| S | 198 | 184 | 171 | 151 | 183 | 202 | 189 | 168 | 170 | 218 | 205 | 184 | 165 | 225 | 213 | 191 |
| W | 360 | 418 | 468 | 551 | 333 | 389 | 438 | 519 | 310 | 364 | 411 | 491 | 300 | 352 | 399 | 478 |

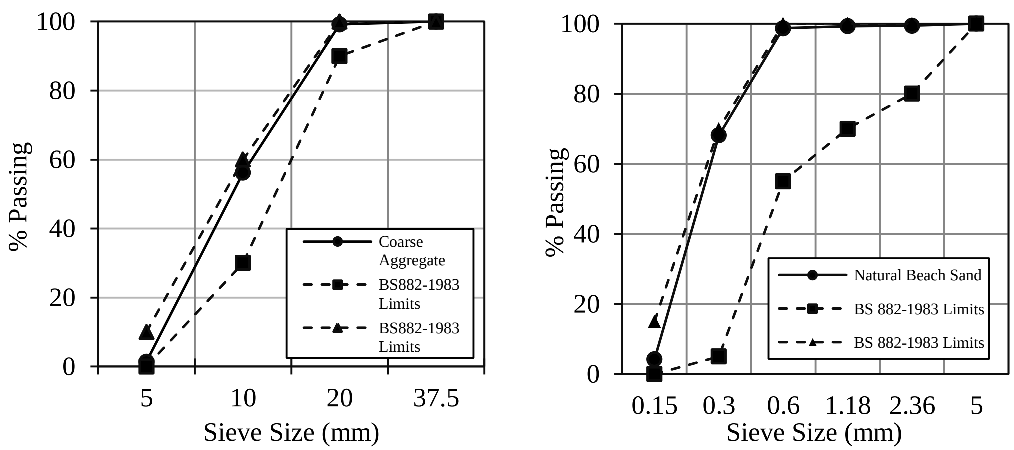



Figure 4: Grading curves for both coarse and fine aggregate.

### 2.3 Mixing Procedures

Paddle-type mixer having a capacity of 0.003m$^3$ was used to prepare all concrete batches. Initially, sand and cement were introduced and mixed on dry condition for not less than 2 minutes to ensure the homogeneity of the blend. Later, water was added slowly to the mixer, and the mixing continued for other three minutes.

### 2.4 Specimen Preparations and Curing

Two series of specimens have been prepared to cover the general objectives of this research program. In the first series, used to investigate both compressive and flexural strength of TSC, and a total of 192 samples through 16 mixes were cast in an average of 12 samples per mix. The second series was employed to investigate the effect of cyclic loading on the energy dissipation of TSC, a total of 128 samples through 16 mixes were cast in an average of 8 samples per mix. Standard cubes of size 150x150x150 mm and standard beams of size 150x150x750 mm were prepared to investigate compressive and flexural strength of TSC respectively. Grout strength was taken as an extra indication of strength and measured using standard cubes of size 100x100x100 mm. Moulds were cleaned and oiled to facilitate easy demoulding and filled first by saturated surface dry aggregate before introducing the grout. The grout was delivered into the preplaced aggregate skeleton under gravity pressure to produce the TSC through hard plastic injection pipe having a diameter of 20 mm and a height of 2 meters. The pipe is lowered to the bottom of the samples and then drawn up when the grout filled the voids in the aggregate Skelton. After 24 hours of the casting process, the concrete samples were removed from the moulds and then immersed in a water tank for seven days. All specimens were then removed from water curing tanks and stored in the laboratory air at 25 $^0$C until testing age at 28 days.

### 2.5 Workability Investigations

Once, the mixing process is done, the workability tests were performed in quick succession. In order to measure the discharging time of known volume of concrete and propagation capacity of the grout, V-funnel and flow-table tests were conducted according to ASTM standards (ASTM C230, 2001; ASTM C939, 2010). Table 2 presents sample of fluidity results of different grout mixes. From the results it is clear that for the same w/c ratio a considerable reduction was recorded for both filling time and grout flow with the increase in the s/c ratio.

Table 2: Fluidity of grout with different mix proportions

| Testing Method | w/c | s/c | | | |
|---|---|---|---|---|---|
| | | 0.5 | 1.0 | 1.5 | 2.0 |
| Flow cone (Sec.) | 0.55 | 94 | 90 | No flow | No flow |
| Flow meter (cm) | 0.8 | 40 | 37 | 35 | 20 |

## *2.6 Compressive and Flexural Strength Investigations*

Flexural and compressive strength of both TSC and grout at the age of 28 days were investigated using the first series of specimens as described earlier in this paper. Universal hydraulic testing machine with maximum capacity of 2200 KN were used. The rate of loading was approximately adjusted at 0.5 KN/sec and 0.05 KN/sec for compressive strength and flexural strength respectively. The test results were calculated as the mean of four samples for each mix as presented in Table 3. The two-point loading for flexural testing is shown in Figure 4. Failure loads were calculated based on modulus of rupture (fr) which is given by the ACI code (ACI Committee 318, 2008), as shown in Equation (1). The flexural strength was, however, calculated in terms of measured failure loads as shown in Equation (2).

$$f_r = 0.62x\sqrt[2]{f'_c} \qquad (1)$$

$$f_r = \frac{MxY}{I} = \frac{PL}{bh^2} \qquad (2)$$

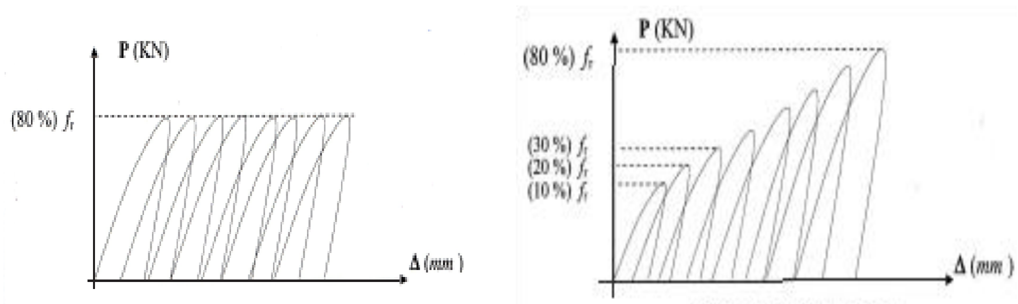
Where, L is the span length, b is the cross section width, h is the section height, and fc` is the compressive strength of concrete. All dimension units in millimeters (mm) and the loading in Newton (N). Detail findings and discussion of the results are presented in other published work (Abdelgader *et al*., 2013).

Table 3: Compressive and flexural strength test results (MPa)

| w/c | 0.55 | | | | 0.65 | | | | 0.75 | | | | 0.80 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| s/c | 1 | 1.25 | 1.5 | 2 | 1 | 1.25 | 1.5 | 2 | 1 | 1.25 | 1.5 | 2 | 1 | 1.25 | 1.5 | 2 |
| fc` | 26.2 | 20 | 20.1 | - | 16.9 | 20.9 | 24 | 24.7 | 17.6 | 19.8 | 19.8 | 16.9 | 14.9 | 13.8 | 12.4 | 18 |
| fcg` | 33 | 38 | - | - | 34 | 29 | 43 | 33 | 26.5 | 27 | 34 | 40 | 28 | 28 | 29.5 | 34 |
| fr | 2.6 | 2.9 | - | - | 2.7 | 2.6 | 3.2 | 2.7 | 2.2 | 2.5 | 2.2 | 2.1 | 2.0 | 2.1 | 2.2 | 1.7 |

## 3.0 Energy Dissipation Testing

In this study the energy dissipation test was measured in flexure using standard beams of size: 150 mm x 150 mm x 750 mm subjected to loading set-up as shown in Figure 3. The rate of loading was 0.05 KN/sec. As explained earlier that a total of 128 beams were tested in this experiment. Sixty four samples were tested under constant cyclic loading while the other sixty four were tested for gradual cyclic loading. In this study the ratio of energy dissipated per cycle to the total input energy, denoted by (Rn), is presented and discussed. The testing model is shown in Figure 5 and a brief description of the testing procedure is presented in the following sections.




(a) Constant Cyclic Load

(b) Gradual Cyclic Load

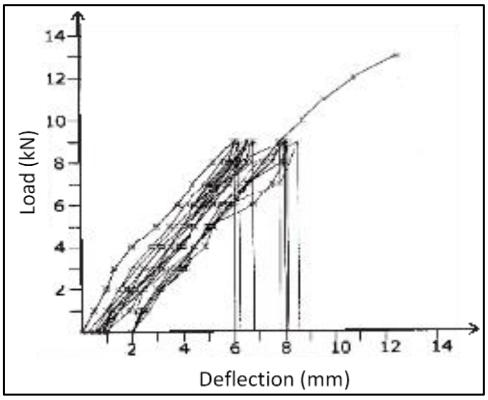
Figure 5: Energy dissipation model for constant and gradual cyclic loading.

### *3.1 Energy Dissipation using Constant Cyclic Loading*

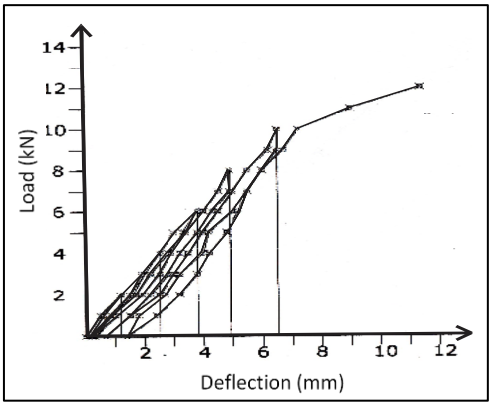
In constant cyclic loading the beams were loaded with a constant rate of loading up to 80% of the failure load as presented in Figure 5a. In each increment of loading the corresponding mid-span deflections were measured. After reaching the maximum loading, the unloading process started and the both load and deflection values were recorded in reverse order with the same rate of loading. This process of loading-unloading (cycle loading) was repeated by the same way for all beams to a maximum of 10 cycles. The load-deflection results are presented in Figure 6. Values of energy dissipation ratio (Rn) were calculated from results and demonstrated in Figure 7a and 7b.

### *3.2 Energy Dissipation using Gradual Cyclic Loading*

In this case, the range of 80% of the failure load was divided into equal increments, each one corresponded to 10% of the targeted failure loads, as shown in Figure 5b. Values of both vertical deflections and corresponding loads been recorded in loading and reloading stages in similar manner to those previously prescribed for constant cyclic loading. Due to the sensitivity of the test and technological limitation, samples were subjected to an average of six cycles. Figure 8 presents the results of energy dissipation ratio (Rn) after a gradual cyclic loading regime. The load-deflection results for gradual cyclic loading are also presented in Figure 6.




a- Constant Loading




b- Gradual Loading

Figure 6: Load deflection values for constant and gradual cyclic loading.

## 4.0 Discussion of Test Results

For constant cyclic loading, results showed that for the same w/c & s/c ratios there has been no significant difference in energy dissipation. Figures 7 and 8 reveal that regardless of the variation in w/c and s/c ratios the results of energy under both constant and cyclic loading are comparable. In terms of Rn values, the rate of energy dissipation in gradual cyclic loading seems to be relatively greater than that of constant cyclic loading, and this could be due to difference in crack initiation, growth and propagations in TSC under those two kinds of loading. It can be seen that as both w/c and s/c ratios increased the energy dissipation is reduced, which is consistent with general relation between strength and w/c. The results further showed that the constant cyclic loading leads to less scattered data, while the gradual cyclic loading system showed an opposite trend. Similar observations made by (Vecchio, 1999), and (Gencoglu and Mobasher, 2010) indicate that that the samples in both ways of loading showed hair-lining cracks developed in the mid of the beams and enlarged vertically from the bottom to the top mid height of the beam before failure moment.

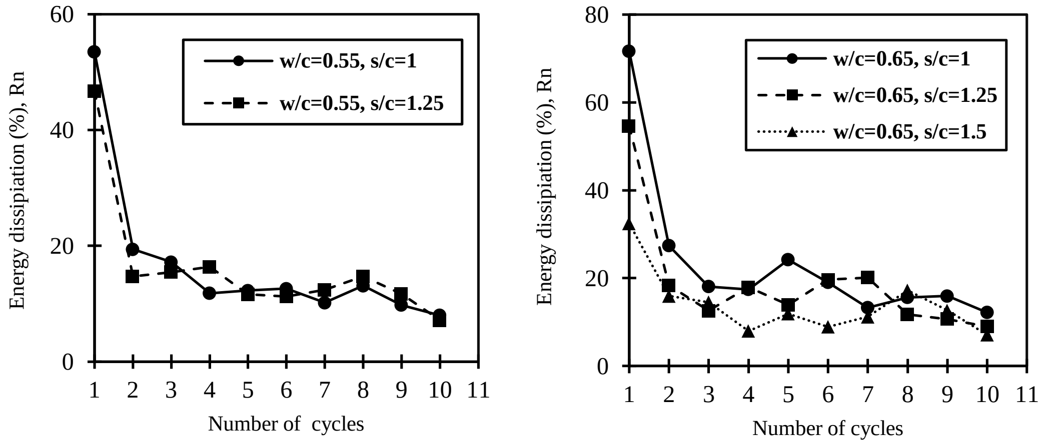



Figure 7a: Energy dissipation ratio (Rn) for TSC samples under constant cyclic loading.

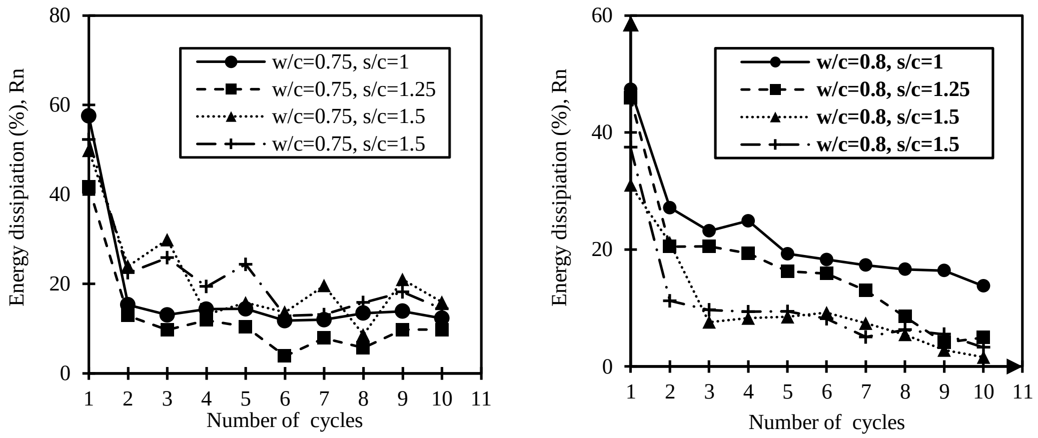



Figure 7b: Energy dissipation ratio (Rn) for TSC samples under constant cyclic loading.

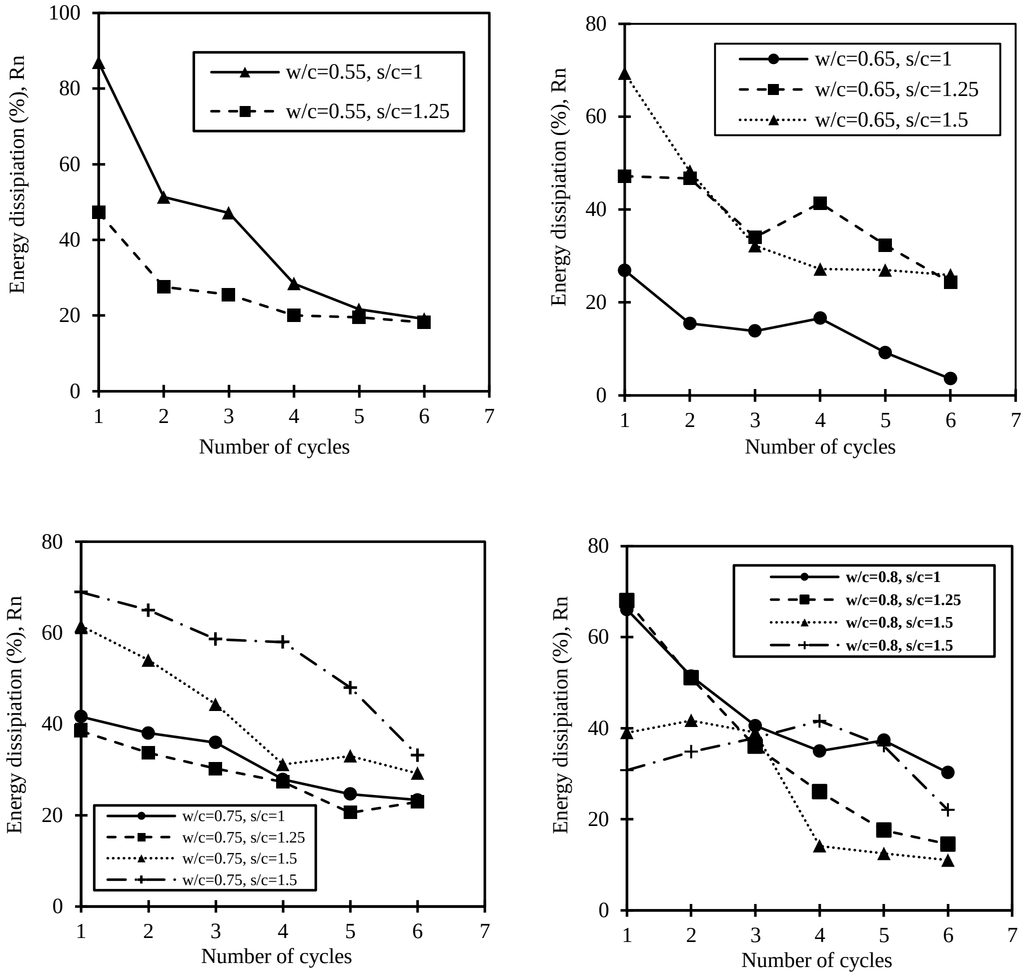



Figure 8: Energy dissipation ratio (Rn) for TSC samples under gradual cyclic loading.

## 5.0 Conclusions

In this paper the energy dissipation in two stage concrete under flexural load has been evaluated. The results obtained and the observations made reveals that the energy under both constant and cyclic loading system are comparable regardless of the variation in w/c and s/c. However, the rate of energy dissipation is slightly higher in the samples subjected to gradual cyclic loading. Owing to the high sensitivity, sudden failures happened after cracking stage. Further study using lower rate of loading with closed loop machine has been put forward as recommendation for better understanding of TSC cracking mechanism and its relation to energy dissipation.

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