6th International Conference on Structural Engineering and Construction Management 2015,
Kandy, Sri Lanka, 11th-13th December 2015

SECM/15/110

Stress-Strain Behaviour of Structural Lightweight Concrete under Confinement

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Abstract: In this study, stress-strain behavior of structural lightweight concrete is studied under unconfined and confined conditions. To this end, the use of naturally occurring perlite material as lightweight aggregate and cement replacement material is considered. Although there are several studies on the confinement effects on normal weight concrete, there is lack of data on the confinement behavior attained for structural lightweight concrete by spiral or stirrup reinforcement. In order to evaluate the performances of structural lightweight concrete and normal weight concrete in a reliable manner, an experimental study is conducted. Through the experimental study on cylinder specimens that are unconfined and confined in different percentages by spiral reinforcement, the elastic and inelastic, namely post-peak behavior of structural lightweight concrete is recorded by the use of displacement-controlled testing machine. The results indicate that concrete produced from perlite as lightweight aggregate as well as through the use of cement replacement material provide significant energy absorption in the presence of spiral reinforcement.

Keywords: Structural Lightweight Concrete; Natural Perlite Aggregate; Cement Replacement Material; Confined Concrete Behavior.

1. Introduction

Concrete type or class considered in the design and construction of load carrying members of structures of civil engineering structures shall have enough strength and adequate ductility with proper reinforcement in order to ensure safety against collapse. In addition to the use of well-known normal weight concrete, the use of lightweight concrete has also been observed in structural applications, after its more popular spread into various aspects of non-structural members in construction industry. In a study conducted with the support of National Science Foundation in U.S. in 1982, the columns made of structural lightweight concrete had been proven to have lateral strength as much as columns made of normal weight concrete. Therefrom in 1983 in the United States the use of lightweight concrete was encouraged in the light of the studies with the release of ACI 318-83 (1983) [1].

Due to the light weight of aggregates used, lightweight concrete reduces the total dead weight of structures advantaging in a significant decrease in the geometrical dimensions of the structural elements, particularly foundations and columns. These reductions could provide savings in terms of structural safety, economy and ease of construction. Furthermore, lower permeability and comparatively high freeze-thaw resistance are taken into account as advantages of structural lightweight concrete.

On this subject, Turkey has a great potential of raw materials to be used as lightweight aggregate due to its geomorphologic structure; as claimed 75% of total worldwide perlite reserves are in Turkey. However the Turkish Specification TS-500 does not allow the use of lightweight concrete in structural load carrying members.

This research in this regards firstly aims to determine the stress-strain behavior of structural lightweight concrete. Although there are several studies on the confinement effects on normal weight concrete, there is lack of reliable information on the confinement behavior attained by structural lightweight concrete by spiral or stirrup reinforcement. The study of Hlaing et al. [2] is one of the remarkable ones investigating confinement effect of lightweight concrete. In their study, they have also noted that there are almost no studies that they can record on the determination of the response of lightweight concrete material’s stress-strain response. In their study, different lightweight concrete samples varying between 38 MPa and 58 MPa were tested with different spiral reinforcements those having tensile stress of 1245, 1457 and 1675 MPa. Although they have performed great effort, since sample spiral spacing was comparatively low and using spiral reinforcement with comparatively high tensile capacity, minimum 1245 MPa as mentioned, they have not been able to conclude with a fair post peak response as observed in standard tests, i.e. the post-peak response of the stress-strain plots from the experiments yielded significant hardening response, which is actually not the most characteristic response that would be studied for concrete material.

While not related to lightweight concrete, the study of Leung and Burgoyne [3] can be cited as one of the remarkable studies on the determination of confinement effects on concrete. Different from their counterparts, they studied the confinement effects attained by aramid fibers. In their first set of experiments, aramid fibers were placed as single spirals with a spiral spacing of 10, 20, 35 and 50 mm, those having elasticity moduli of 90.1 GPa. In the second set, in order to visualize the confinement effect of non-circular elements, two different spirals were placed to be interlocked. The concrete in that study has been molded with design strength of 40 MPa.

In the light of experiments, they have concluded that the load versus displacement of the specimens merely differed from each other before reaching the peak load, for unconfined and confined ones. Furthermore, the ultimate strain was 4 times greater for 50 mm spaced spirals, and 7.5 times greater for 10 mm spaced spirals, than the unconfined specimens.

In order to visualize the success of the aim of the study in this research paper, the authors performed a trial testing on unconfined and confined lightweight concrete at Materials of Construction Laboratory of Middle East Technical University. As seen in Figure 1, confinement has a great effect on both maximum compressive stress and ultimate strain. In addition, the balance between the concrete and spiral reinforcement is proven to be successful to give a softening post-peak responses.

In a companion paper by Kent and Park [4], the theoretical model herein is compared with results of the experimental program carried in this research study, as well.

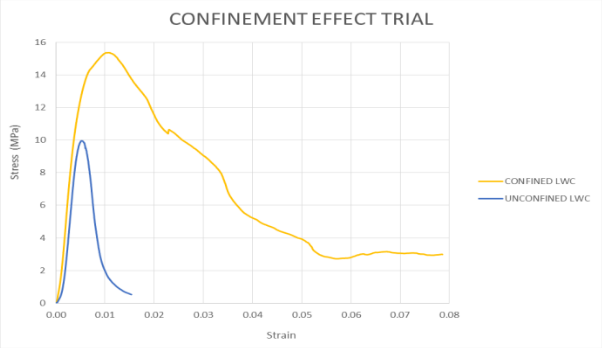

Figure 1. Early Trials on Confined LWC

2. Materials

In the experimental study, the tests are applied on three different types of concrete, naming, normal weight concrete, lightweight concrete and modified lightweight concrete. The concrete types differ from each other in some aspects. As in normal weight concrete crushed limestone aggregates are used whereas natural perlite aggregates are used for lightweight and modified lightweight concrete. To study the effect of perlite powder as a binder, in the modified lightweight concrete, 50% of the amount of cement is replaced with perlite powder.

2.1 Properties of Materials

The lightweight aggregate to be used in the scope of this paper, perlite, is found in raw form in Mollaköy, Erzincan, which is an earthquake prone region in Turkey. The Mollaköy perlite has been shown by Aşık [5] and Eser [6] to be usable as lightweight aggregate after few physical processes. The properties of the aggregate and its powder are presented in Table 1 and Table 2 as obtained from the studies of Asik and Eser.

Furthermore, Table 3 below lists the properties of limestone aggregates used in normal weight concrete.

Apart from aggregates types, in all the concrete mixtures, the same Portland cement of type CEM I 42.5 R is used. The chemical and physical properties of which are cited in Table 4 below.

Furthermore, BASF Gilenium 51 is used as superplasticizer in a ratio of 1% by mass. The properties of BASF Gilenium 51 are cited in Table 5.

Table 1. Physical Properties of Perlite Aggregate

Aggregate Size (mm)	0-3	8-12
Dry-Loose Unit Weight (kg/m3)	1288	1002
Oven Dry Specific Gravity	2.06	1.93
Saturated-Surface Dry Specific Gravity	2.18	2.04
Water Absorption Capacity (%) – 72 hr	5.64	5.59
No.200 Sieve % Passing	11.64	-
Los Angeles Abrasion (%)	-	49.7

Table 2. Chemical and Physical Properties of Perlite Powder

Chemical Composition of Perlite Powder	
SiO2	70.96
Al2O3	13.40
Fe2O3	1.16
MgO	0.28
CaO	1.72
Na2O	3.20
K2O	4.65
Loss on ignition	3.27
Physical Properties of Perlite Powder	
Specific Gravity	2.38
Fineness	
Passing 45-µm (%)	80
Specific Surface, Blaine(m2/kg)	413
Median Particle Size (µm)	19.1
Strength Activity Index (%) *	
7 Days	78
28 Days	80

Table 3. Physical Properties of Limestone Aggregate

Aggregate Type (mm)	0-4	4-12	12-25
Saturated-Surface Dry Specific Gravity	2.62	2.71	2.71
Oven Dry Specific Gravity	2.59	2.70	2.70
Water Absorption Capacity (%)	1.4	0.29	0.22

Table 4. Chemical and Physical Properties of Portland Cement

CEM I 42.5 R	
Chemical Composition, %	
CaO	62.54
SiO2	19.32
Al2O3	4.76
Fe2O3	4.36
MgO	2.04
SO3	3.49
K2O	0.67
Na2O	0.21
Cl-	0.0219
LOI	2.26
IR	0.63
Physical Properties	
Specific Gravity	3.17
Blaine Fineness, cm2/g	4534
Initial Set, min	115
Final Set, min	160

Table 5. Properties of Superplasticizer

Structure of Material	Polycarboxylic ether based
Density	1.082 - 1.142 kg/lt
Chlorine Content	< 0.1%
Alkaline Content	< 3%

The reinforcing steel used as spiral confining reinforcement has a diameter of 4 mm that will help in demonstrating the confinement properties properly. The steel wires were tested in universal testing machine, and its stress-strain performance is presented in Figure 2. The tension test resulted in a yield strength of 226 MPa and ultimate strength of 351 MPa.

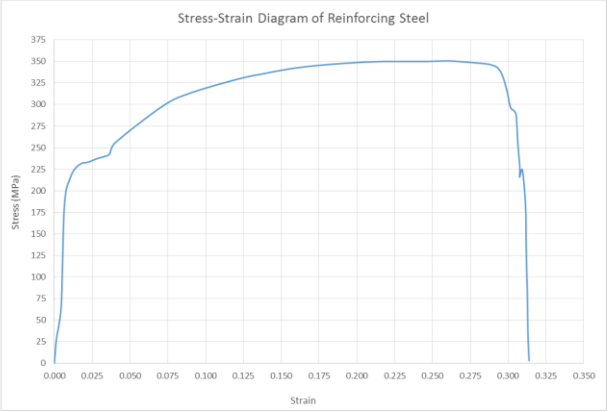

Figure 2. Stress-Strain Diagram of Reinforcing Steel

2.2 Specimens and mix proportions.

The samples prepared for the tests are molded in 10×20 cm cylindrical specimens. The tests will be applied on unreinforced and two types of reinforced samples; with 30 mm spaced spiral reinforcement and 50 mm spaced spiral reinforcement. To not violate the clear cover of specimens, all the reinforced samples are provided with 1 cm clear cover. With the help of wooden sticks the clear cover is provided for both the top and the bottom of each specimen.

To reduce the error of experiments, for each type of specimens the results will be evaluated as the average of 3 tested samples.

The concrete mixture composition is designed to obtain 20 MPa compressive strength at the time of testing. In order to monitor the progress in a successful manner, the specimens are tested in seven days intervals. For the unconfined concrete samples that reach a compressive strength close to 20 MPa, their successor spirally confined samples start to be tested. The composition of concrete mixture is presented in Table 6

Table 6. Mixture Proportions of Concretes

Mix Proportions (kg/m3)			
Concrete Type	NWC	LWC	MLWC
Cement	250	250	125
Perlite Powder	0	0	125
Water	133	202	202
0-3 mm Perlite Aggregate	0	883	883
8-12 mm Perlite Aggregate	0	657	657
0-4 mm Limestone Aggregate	1111	0	0
4-12 mm Limestone Aggregate	421	0	0
12-25 mm Limestone Aggregate	526	0	0
Superplasticizer	2.5	2.5	2.5

Table 7. Properties of Fresh Concrete

Concrete Type	W/C	Slump (mm)	Air-Content (%)	Density (kg/m^3)
NWC	55	85	2	2410
LWC	80	100	2.5	1913
MLWC	80	90	2.2	1910

After the preparation of the concrete mixtures, various fresh concrete tests are performed to measure and evaluate the workability, durability and integrity of the mixtures. The results obtained from the tests are presented in Table 7.

In the light of results obtained from fresh concrete samples, the removal time of cases of normal weight concrete is 24 hours after pouring of concrete while for lightweight concrete and modified lightweight concrete is 48 hours after pouring. In order to prevent the dehydration of fresh concrete, humid blankets are used. After removing the molds, the specimens are left for curing in the curing pool of 21 °C in the Construction Materials Laboratory.

3. Tests and Results

3.1 Normal Weight Concrete

In the experimentation of normal weight concrete specimens, concrete gained early strength in a couple of days as expected due to the use of rapid setting cement type. Accordingly, the unconfined specimens tests started in the 3rd day, after which, the confined specimens were tested a day later, both at a loading rate of 1mm/min.

The peak strength observed in unconfined samples is about 16 MPa, this value was considered to be an acceptable level of peak strength gained, where the strain at peak strength is observed as 0.0038. On the other hand, the confined samples with 30 mm spiral spacing had a peak strength value of 17.7 MPa, with a strain of 0.006. The energy absorbed at the ultimate strain is calculated as 1709 kN.mm. Next, 50 mm spiral spaced confined normal weight concrete samples are tested. The maximum strength is recorded as 16.7 MPa with a strain of 0.0055 at this point. The energy absorbed at the ultimate strain, $\varepsilon c20$, is calculated as 802 kN.mm. The stress-strain diagrams, regarding the average of three samples, for unconfined and confined with 30 mm and 50 mm spiral spaced concrete samples are presented in Figure 3.

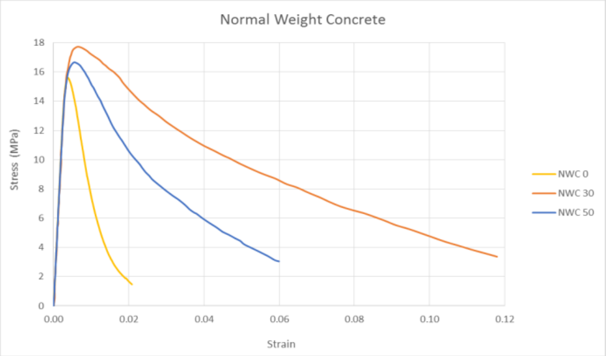

Figure 0. Stress-Strain diagram of Normal Weight Concrete

The results obtained from the series of experiments are compared with the theoretical calculations, those obtained in the light of Kent and Park Model [4]. The theoretical and experimental results differed from each other in some respects. In the experimentation of 30 mm spiral spaced concrete, maximum stress achieved is 6% smaller than the theoretical results, whereas the strain at the ultimate stress is 30% greater than the theoretical calculations. Similarly, the maximum stress for the 50 mm spiral spaced concrete is 5% smaller than the theoretical calculations, with a 28% smaller strain at the point of maximum stress.

Additional samples are tested 180 days later in order to observe the strength gain behavior of unconfined and confined normal weight concrete. Unconfined specimens gained strength to reach an average peak stress of 41.53 MPa, confined specimens with 30 mm and 50 mm spiral spacing showed near results of 41.88 and 41.39 MPa peak stresses, respectively.

3.2 Light Weight Concrete

In the case of lightweight concrete, the concrete specimens were tested starting from the 7th day as anticipated to reach the expected results. The maximum load carrying capacity is recorded as 133.5 kN and 17 MPa with a strain of 0.0042. The strain and stress experienced are in line with the predicted results.

As unconfined samples reach strength of 19 MPa, confined samples tests started. In Figure 4, relevant stress-strain diagrams are presented for unconfined and confined concrete with spiral spacing of 30 mm and 50 mm. The test set up and experimentation is presented in Figure 5. The peak strength of unconfined lightweight concrete samples is recorded as 19 MPa with a strain of 0.0046. Successively, the confined concrete samples are being tested under compression with a loading rate of 1 mm/min. The peak strength observed in the test of 30 mm spiral spaced samples is recorded as 20.6 MPa with a strain of 0.006. The energy absorbed at the ultimate strain is calculated as 776 kN.mm. Following the 30 mm spiral spaced samples, 50 mm spiral spaced concrete samples are tested. The maximum stress is recorded as 19.88 MPa with a strain of 0.0054. The energy absorbed, according to the results mentioned, is observed as 498 kN.mm.

The results obtained from the experimentation are compared with the theoretical calculations based on Kent and Park Model. For 30 mm spiral spaced samples, the ultimate stress experienced is 9% smaller than the theoretic calculations, whereas the strain at ultimate load is 20 % greater than the theoretic calculations. The results observed for 50 mm spacing do differ from the results of 30 mm spiral spaced samples. The ultimate stress is 6 % smaller than the theoretical calculations. While, the strain at the ultimate load for 50 mm spiral spaced is 8% greater than the theoretical calculations.

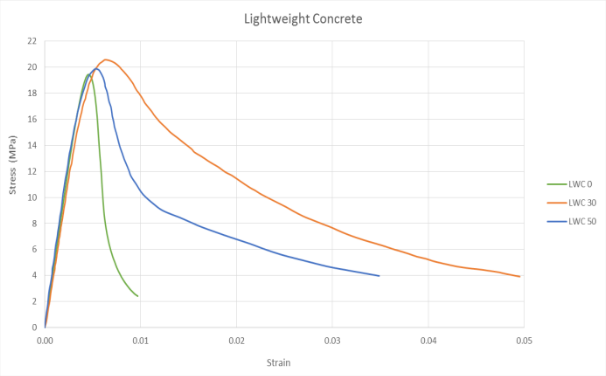

Figure 4. Stress-Strain diagram of Lightweight Concrete, 11 Days

Figure 5. Test Set up and Experimentation

As a later step, similar specimens in this group are tested 180 days later. Unconfined specimens showed an average maximum compressive strength of 32.95 MPa. Yet, while confined specimens with 30 mm spacing showed higher results, 35.40 MPa compressive strength, samples with 50 mm spaced confinement showed relatively close average result of 31.87 MPa.

3.3 Modified Light Weight Concrete

The compressive strength of modified lightweight concrete samples is tested in several days. These experiments were conducted on the 7th, 14th, 21st, 28th and 42nd days. Being close to the results expected, the final tests are conducted on 42nd day.

The compressive strength of modified lightweight concrete has increased day by day after moulding. As seen in the Figure 6, the compressive strength has increased from 7 MPa to 15 MPa between 7th and 42nd days. Similarly, its elasticity modulus increased approximately double of its value from 7th day to 42nd day. As seen in Figure 7, the unconfined sample of modified lightweight concrete reached a compressive strength of 15.37 MPa with a strain of 0.005 relatively. The ultimate strain reached demonstrates the great energy absorption capacity of modified lightweight concrete.

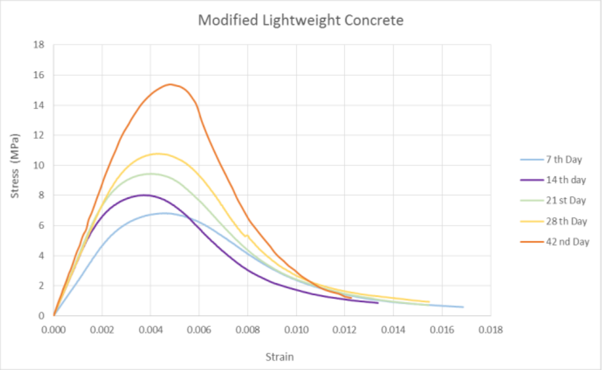

Figure 6. Stress-Strain diagram of Unconfined Modified Lightweight Concrete

In the next step, confined samples of modified lightweight concrete are tested. Initially, the samples with 30 mm spiral spacing are tested. The samples tested have reached an average value of 17.6 MPa with a strain of 0.008. The energy absorption capacity of the sample is calculated as 1159.55 kN.mm. Then, the confined samples of 50 mm spiral spacing are tested. The samples have an average compressive strength of 16.23 MPa with a strain of 0.006. The energy absorption capacity is calculated as 499.93 kN.mm. The overall results of tests performed on modified lightweight concrete are presented in Figure 7. The results of modified lightweight concrete are compared with the Kent and Park Model, as well.

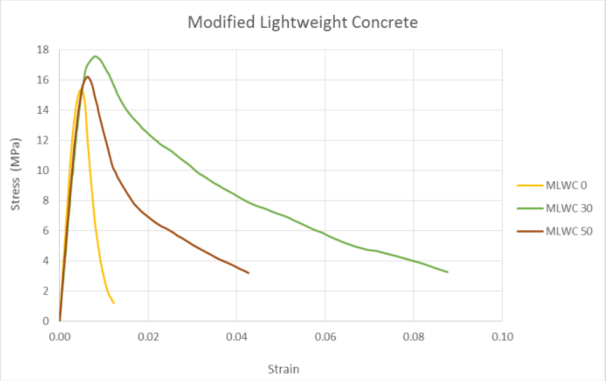

Figure 7. Stress-Strain diagram of Modified Lightweight Concrete

In the case of samples with 30 mm spiral spacing, the experienced ultimate stress is 6% smaller than the theoretical calculations. On the other hand, the samples experienced a strain of 26% greater than the theoretical calculations. Similarly, the 50 mm spiral spaced specimens have 6% smaller ultimate stress with 12% greater strain, when compared with the theoretical calculations.

To study the behaviour of confined perlite modified light weight concrete in long periods; additional specimens are tested in deformation controlled machine at 180 days. The samples with both spiral spacing showed a significant increase in the peak compressive strength. As can be seen in Figures 8 and 9, 30 mm spaced specimens showed peak strength of 21.53 MPa and 50 mm spaced specimens resulted with 20.51 MPa.

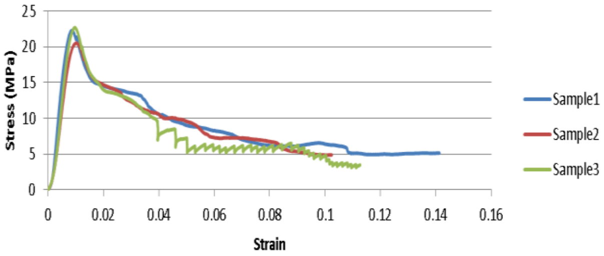

Figure 8. Stress-Strain diagram of Modified Lightweight Concrete with 30 mm spaced spirals.

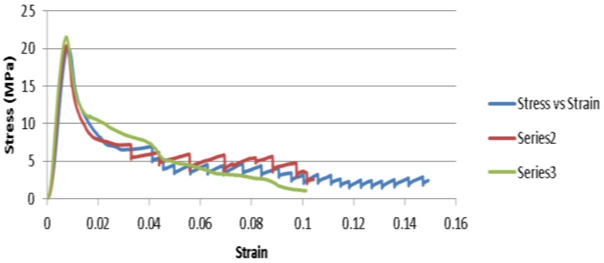

Figure 9. Stress-Strain diagram of Modified Lightweight Concrete with 50 mm spaced spirals.

4. Conclusion

In the light of experimental studies on cylinder specimens, it is concluded that lightweight concrete and modified lightweight concrete have comparatively weaker performance in terms of ultimate strain and energy absorption capacities, but with the presence of spiral confinement provides significant increase in energy absorption for these materials. The performance of lightweight concrete as a structural material cannot be disregarded in terms of its ultimate strength and relative strain values. Although use of lightweight concrete is prevented in some structural codes, through the experiments performed, it is conspicuous that lightweight concrete can reach the required mechanical and physical properties easily. In this respects, limitations on the use of lightweight concrete does only prevent the advances in the area and discourage the attention of both researchers and designers. Through further studies and advances in lightweight concrete, it will be fair to realize that lightweight concrete is a reliable construction material even for structural purposes as normal weight concrete is.

5. References

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