Experimental and numerical studies of impact behavior of fiber lightweight aggregate concrete

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ABSTRACT

After the 9-11 attack, protection of iconic, strategic and public structures subjected to impact and explosive loadings has been a major topic of research, which also involves with progressive collapse, thermal effects, damage analysis and advanced material technologies. The demand for Light Weight Aggregate Concrete (LWAC) in many recent applications is increasing owing to the fact that lower density of structural material leads to lower gravitational loading of structures and consequently lower earthquake forces. Nevertheless, LWAC usually suffers from low ductility similar to other brittle materials. A remedy is to add fibers to increase the ductility and energy absorption.

As these lightweight constructions may be subjected to impact loadings during life time period, investigating the impact behavior of concrete structures is necessary. A few studies were performed on impact behavior of normal fiber reinforced concrete. Nonetheless, there is no report on impact behavior of fiber reinforced lightweight aggregate concrete.

In this research, cylindrical fiber lightweight aggregate concrete samples with 150 mm diameter and 60 mm thickness are exposed to low velocity impact load (according to the standard of ACI 544-2R "impact test on fiber reinforced concrete") and compared with plain concrete samples. Coarse pumice aggregates were used in concrete. Also, polypropylene was utilized in mixtures proportion of concrete.

In addition to experimental approach, a numerical simulation has been performed to analyze the test specimens under impact loadings using the LS-DYNA finite element software. Comparison of numerical predictions with experimental results illustrates fairly good agreement.

Keywords: *crack opening, fiber, impact, LWAC*

1- INTRODUCTION

Structural lightweight aggregate concrete (LWAC) has been used in many civil engineering applications as a convenient alternative to conventional concrete. As a matter of fact its lighter weight permits a saving in dead load with a reduction in the costs of both superstructures and foundations. In addition, the better thermal insulation, the greater fire resistance and the substantially equivalent sound-proofing properties make it preferable correspond with normal weight concrete (NWC) for nonstructural applications. In the last five decades, the use of LWAC has been extended to structural elements, thanks to the improvement in performances obtainable by means of appropriate ingredient mix proportions [Demirboga *et al.*, 2001] and appropriate design of the reinforcement. Furthermore, the reduced weight may make LWAC a major option for structures in seismic zones, because of the reduced dynamic actions. In addition, it is used for precast structures because of making it easier to move the elements to be connected. Although LWAC has various advantages, it has a brittle behavior which is not appropriate in structural elements. Adding fibers to the lightweight weight aggregate has been proposed to enhance this drawback.

Most fibers which are added to concrete are manmade, and can be classified into two main categories: metallic (such as steel) or synthetic (such as polypropylene). Although steel fibres are dominant in the field of fiber reinforced concrete (FRC), polypropylene fibers have proved to provide high efficiencies in many practical applications [Parameswaran, 1991]. Polypropylene fibres are capable of improving the ductility of concrete by enhancing properties such as its flexural toughness and impact resistance [Soroushian, 1996].

Current understanding of the impact resistance of FRC concrete is very limited. Especially there are no researches on the impact behavior of polypropylene fiber reinforced light weight aggregate concrete (PPLWAC). At the heart of the problem is the absence of a standard test technique for impact loadings. Several investigators have used different impact machines, specimen configurations, and instrumentation; in addition of adopting differing analysis schemes. Much still remains to be done both towards the development of a standard technique and towards generating fundamental understanding of concrete performance under impact loadings [Bindiganavile, Banthia and Aarup, 2002].

Nowadays, structural behaviors under different applied loads or boundary conditions are increasingly predicted by computational tools and softwares. Several softwares such as ANSYS, ELFEN, ABAQUS, LS-DYNA, and AUTODYN are available to simulate full impact and explosion loadings on a structure.

This research consists of two parts of experimental program and numerical simulation. In the first part the procedure of making PPLWAC samples, mix proportions, and impact tests are described. The second part discusses the numerical simulation of the performed impact tests. Finally the results from the experimental and numerical simulations are compared and described.

2- EXPERIMENTAL PROGRAM

2-1- Materials and Mix Proportions

In this study, crushed pumice used as coarse lightweight aggregate. The apparent density of dry aggregate was 430 Kg/m3. The maximum nominal size of coarse aggregate was 16 mm. Natural sand with limestone base with a maximum nominal size of 6.0 mm was used for fine aggregate in mixture proportions. Fine aggregate had a fineness modulus of 3.1 and specific gravity of 2.6 gr/cm3. Normal Portland cement (ASTM type II) was used in all mixtures. Chemical components of cement are presented in Table 1.

Polypropylene (PP) fiber was used in this study to investigate enhancement effect of PP on the lightweight aggregate concrete impact resistance. The properties of PP are shown in Table 2.

Low costs and being well known conventional fiber are the two major reasons for using pp fibers.

Component	SO3	K2O+Na2O	MgO	CaO	Fe2O3	Al2O3	SiO2
Percentage	2.4	0.25+0.04	1.3	66.2	3.0	5.1	21.1

TABLE 1 - CHEMICAL COMPONENTS OF CEMENT

Fiber	Density (Kg/m3)	Length (mm)	Diameter (mm)	L/D	ft (MPa)	Shape
Polypropylene	900	12	0.03	400	450	Straight

TABLE 2 - PROPERTIES OF PP FIBER

Two types of concrete with 0.0 % and 0.4 % PP fiber are made. The impact results of fiber reinforced lightweight aggregate concrete are compared with the reference no fiber mixtures. As the fibers substantially decrease the workability conditions, polycarboxylic base superplasticizer was used to improve the slump and workability of concrete. Details of mixtures properties are presented in Table 3.

No.	Cement (Kg/m3)	Sand (Kg/m3)	Lightweight Aggregate (Kg/m3)	Superplasticizer (% of Cement Weight)	PP Fiber (Kg/m3)
PP0	500	800	450	1.0	0
PP1	500	790	450	1.0	3.6

TABLE 3 - MIXTURE PROPORTIONS

Before mixing, a few percentages (water absorption of lightweight aggregate) of mixture design water were added to the dry coarse aggregate and kept for ten minutes. Afterwards, coarse and fine aggregate, cement, water and superplasticizer were mixed together for two minutes. At the end, fibers added to the mixture and mixed for eight minutes. For testing the impact resistance of reinforced lightweight aggregate concrete. For each mixture design, six 150 mm cubes and three150×300 mm cylinders were cast. Cubes were used for determination of compressive strength in 3, 7 and 28 days. Two cylindrical specimens were used for the Brazilian tensile strength test.

Also, one cylindrical specimen was cut into three disks of 60 mm height. The presented results of the impact test are the average predictions of three specimens. All specimens were demolded after one day and then cured in the water for 28 days at the water temperature of 23 ± 1°C.

2-2- Impact Test

Several impact tests such as Charpy Pendulum, penetration impact, Hopkinson rod and drop weight test have been developed to define the impact resistance of concrete. Each has few advantages as well as a number of shortcomings. Among them, the drop weight test which is simple and less expensive is adopted in this study. The number of impacts necessary to cause prescribed levels of distress in the test specimen serves as a qualitative estimate of the energy absorbed by the specimen at each level.

The present test is performed according to the ACI 544 report. The equipments of the test are a standard; manually operated 4.54 Kg compaction hammer with a 457 mm drop, 63.5 mm diameter hardened steel ball and a flat base plate with positioning bracket. The hammer dropped repeatedly, and the number of impacts associated with the first visible crack on the top and to cause ultimate failure is both recorded. The drop weight test setup is shown in Figure 1.

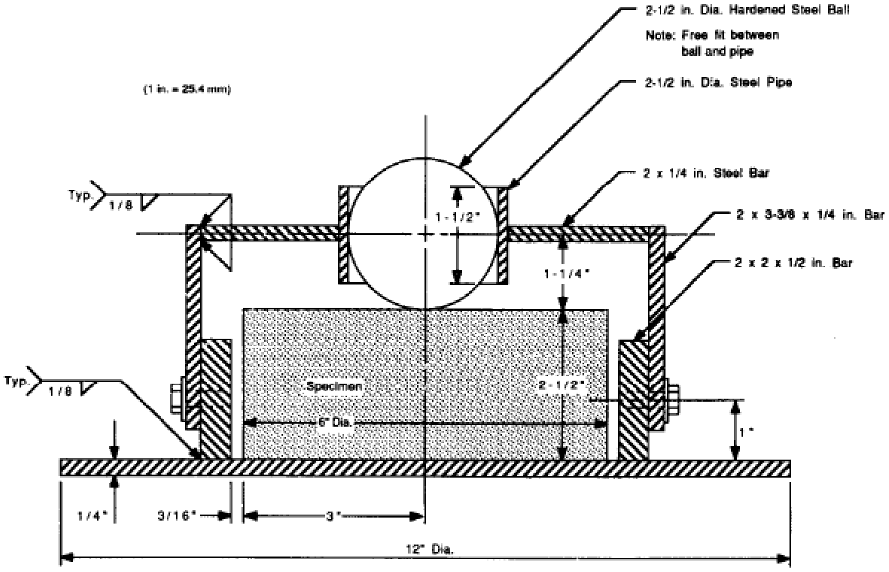

FIGURE 1 - DROP WIGHT TEST SET UP

In this research crack patterns are examined immediately after each impact. The number of strikes in which the first crack appears in the specimen is recorded. Increasing the number of strikes, results indicate an increasing in crack propagation and crack widths. The test process is terminated when the maximum crack width in the specimen exceeds the limit 25 mm. The number of recorded impact in this step is considered as the final number of strikes that the specimen can tolerate.

3- RESULTS AND DISCUSSION

The compressive strength in 3, 7, 28 days and the tensile strength of specimens are presented in Table 4.

	Compressive strength (MPa)			Tensile strength(MPa)
Code	3 days	7 days	28 days	28 days
PP0	12.7	15.4	17.1	2.1
PP1	14.9	18.8	20.4	1.7

TABLE 4 - MECHANICAL PROPERTIES OF SPECIMENS

The PP0 specimen tolerated one and two strikes for the first and final cracks respectively. The results show that adding 0.4% PP fiber to the plain concrete increases the impact resistance of concrete. Two and six strikes were tolerated by the fiber reinforced lightweight concrete. In another word, due to an enhancing in tensile behavior with increasing fibers, the capacity of energy absorption and the impact resistance increase.

The results show that the tensile failure was predominate in both types of specimens. Furthermore, in PPLWAC specimens crippling existed in spite of plain specimen. At the first strike in plain concrete, some tensile cracks were generated across the specimen and extended to tensile failures at the second strike.

In PPLWAC specimens, two kinds of failure were observed. Some of specimens fractured into three parts and some others broken into two parts, as depicted in Figure 2.

FIGURE 2 - FAILURE PATTERNS OF SPECIMENS

4- NUMERICAL SIMULATION

4-1- FE software

Several finite element softwares are available to model structural behavior under dynamic loadings such as ANSYS, ELFEN, ABAQUS, LS-DYNA, and AUTODYN, which also include various types of material models for concrete. In this study, LS-DYNA in adopted to simulate the performed experimental tests.

4-2- Geometric Modeling

The PPLWAC specimen and rigid constraints were modeled by hexagonal elements, while projectile was simulated by tetragonal mesh. The total number of constant solid elements in FE-model was 46865, as indicated in Figure 3.

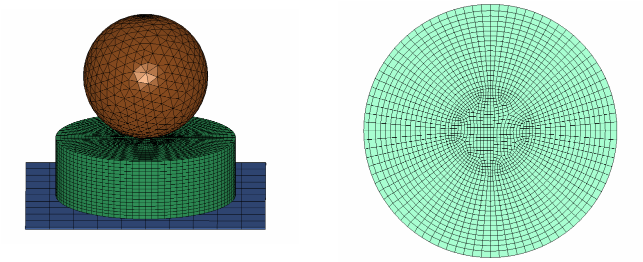

FIGURE 3 – THE FINITE ELEMENT MODEL OF THE SETUP (LEFT) AND THE CONCRETE SPECIMEN (RIGHT)

4-3- Impact Modeling

The projectile strikes the concrete target with a 3.13 m/s velocity which is equivalant to the velocity of a half a meter free fall. The contact between the projectile and the target and also between the target and the constraint is defined by CONTACT-AUTOMATIC-SURFACE-TO-SURFACE option.

Three distinct methods for handling the treatment of sliding and impact along interfaces have been implemented in LS-DYNA, which are referred to as the kinematic constraint method, the penalty method and the distributed parameter method. In this research only the penalty method was used.

The major difficulty in solving the contact problem is the assignment of the value of the penalty stiffness which affects the accuracy and stability of the solution. The use of an excessively high value of the penalty stiffness may lead to numerical errors. The penalty algorithm has another drawback that an increase of the penalty stiffness reduces the stable time increment. On the other hand, smaller values of the penalty stiffness could lead to wrong solutions; excessive interpenetration and incorrect estimates of the stick regions. In order to set the proper value of penalty stiffness factor for the master and slave surfaces, several runs were conducted [Meo *et al.* 2003]. The value assigned to our finite element model was 0.9 because of rigidity of projectile and brittle behavior of concrete.

To model periodic impact loadings, the restart analysis option was used. The results obtained after completion of each strike were used as an input to the next analysis, in which a new strike was defined.

4-4- Material Modeling

4-4-1- Concrete Model

There are several concrete models implemented in LS-DYNA, which include phenomena such as erosion, effect of strain rate, cracking, etc. The "Winfrith Concrete Model" is a three-invariant, four-parametric model based on models by Broadhouse and Neilson 1987, and Broadhouse 1995 but with the strain rate effect included as internal enhancements of the uni-axial strengths and the modulus of elasticity according to recommendations by CEB. The model has advantageous for design purposes; since the parameters used are based on standard static tests and the model has been validated for a number of cases such as blasts and impacts [LSTC, 2006].

New developments and improvements of model "Pseudo Tensor Concrete/Geological Model" are presented by Malvar *et al.* [1997] with the source code. The enhanced damage model is "Concrete Damage" material model which is used to analyse buried steel reinforced concrete structures subjected to impulsive loadings. A full description of tensile and shear damage parts is given in Govindjee, Kay and Simo 1994, 1995 as "Brittle Damage Model". This model also has the advantage of using only a few material parameters [LSTC, 2006].

In this research, however, the soil-concrete material model (TYPE78) was used. Features such as perceiving pressure versus volumetric strain as an equation of state, compressive and tensile yield stress versus different confined pressures, residual strength after cracking, pressure cutoff for tensile fracture which is equivalent to pullout strength in fiber reinforced concrete, and the erosion option make this material model appropriate for modeling both fiber reinforced and plain concretes.

The material parameters used in FE-model are shown in Table 5. The curve for yield stress versus pressure (LCYP) shown in Figure 4 was computed based on Girin and Anoglu research [2007]. Both curves for plastic strain at which fracture begins versus pressure (LCFP) and plastic strain at which residual strength is reached versus pressure (LCRP) are taken from Agardh and Lain [1999], see Figure 5. For the curve of pressure versus volumetric strain, data from tests of concrete specimens by Gregsson [1992] were used with a uniaxial compressive strength of 35 MPa and modulus of elasticity E=34 GPa, see Figure 6.

Parameter	Plain concrete	PPLWAC Concrete
Density (kg/m3)	2100	2200
Shear modulus (GPa)	11.03	10.98
Modulus of elasticity (GPa)	26.48	27.57
Bulk modulus (GPa)	14.71	16.41
Poisson's ratio	0.20	0.22
Pressure cutoff (MPa)	0	-2.1
Residual strength factor after cracking	0	0.5

TABLE 5 - INPUT DATA FOR SOIL-CONCRETE MATERIAL

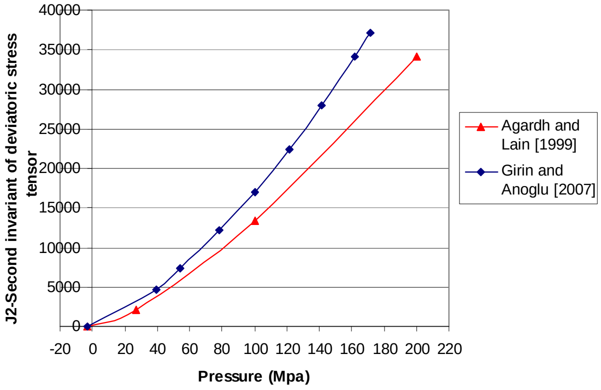

FIGURE 4 - YIELD STRESS VERSUS PRESSURE (LCYP)

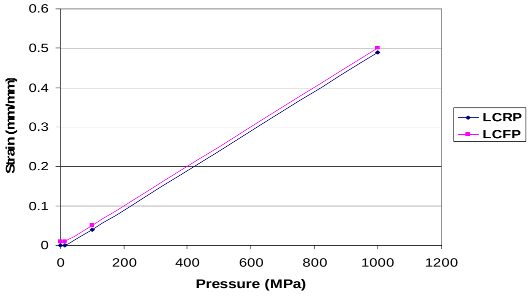

FIGURE 5 - PLASTIC STRAIN AT WHICH FRACTURE BEGINS VERSUS PRESSURE (LCFP) AND PLASTIC STRAIN AT WHICH RESIDUAL STRENGTH IS REACHED VERSUS PRESSURE (LCRP) (TAKEN FROM AGARDH AND LAIN RESEARCH [1999])

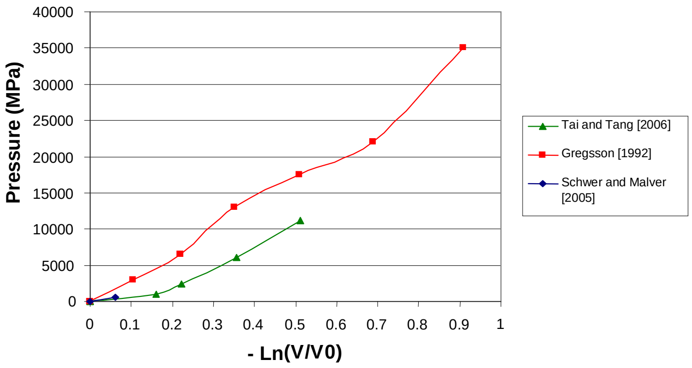

FIGURE 6 - PRESSURE VERSUS VOLUMETRIC STRAIN (EOS), OBTAINED FROM TESTS OF CONCRETE SPECIMENS BY GREGSSON [1992], TAI AND TANG [2006], AND SCHWER AND MALVER [2005]

4-4-2- Constraint and projectile model

Since the material of constraint and projectile was steel and they were exposed to low velocity impact which cannot cause steel to reach the yield stress, an elastic model was adopted using the mat-elastic option with density, modulus of elasticity, and Poisson's ratio equal to 7800 kg/m^3, 2.1×10^6 kg/cm^2, and 0.3, respectively.

5- RESULTS AND DISCUSSION OF NUMERICAL SIMULATION

The finite element analyses were performed by high speed computers in the High Performance Computing Lab, University of Tehran. The total CPU process time required for simulation of plain concrete was about 1 hour. For PPLWAC it took about 2 hours because of modeling four restart analyses in order to simulate four strikes. Von Mises stress contours for the instant of strike and after it corresponding to 0.699 and 0.899 millisecond respectively have been shown in Figure 7. Moreover, Von Mises stress contours and its distribution around the crack has been indicated in Figure 8.

Plain concrete specimens failed in two strikes and the preliminary tensile crack was observed at the egde of the model in the first strik. The failure pattern shown in Figure 9 is similar to the experimental results, in the sense that both of them show the specimen divided into two parts.

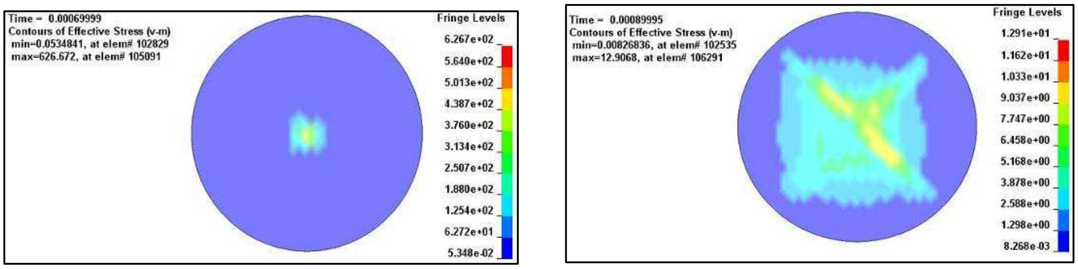

FIGURE 7 - VON MISES STRESS CONTOURS AT THE 0.699 AND 0.899 MILLISECOND

The number of strikes endured by PPLWAC FE-model was four while the first crack was occured in the first strike. Although during the strikes both tensile cracks and crippling phenomena were observed, the tensile failure was the dominant failure pattern, as depicted in Figure 10.

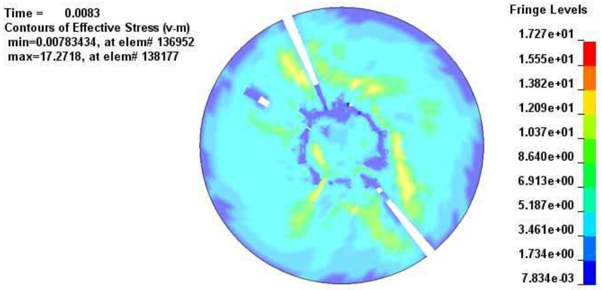

FIGURE 8 - VON MISES STRESS CONTOURS

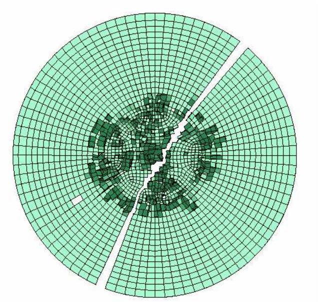

FIGURE 9 – FAILURE PATTERN FOR PLAIN CONCRETE TAKEN FROM FE-MODEL

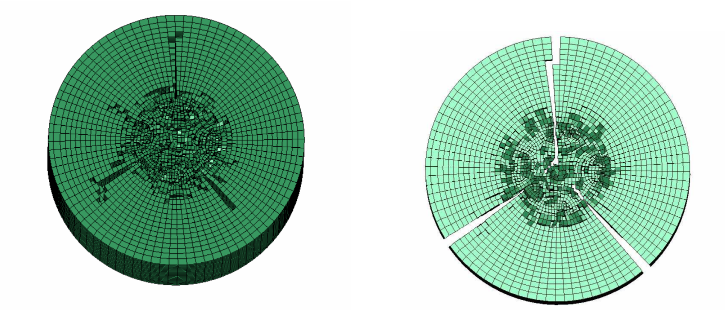

FIGURE 10 – TENSILE AND CRIPLING CRAKS AT FIRST STRIKE (LEFT); DOMINANT TENSILE FAILURE (RIGHT) FOR PPLWAC FE-MODEL

6- CONCLUSION

According to the results taken from experimental tests and the FE-model, the following conclusions can be drawn:

- Adding PP fiber to the plain concrete increases the impact strength; which PP fiber enhances the impact resistance approximately three times of the ordinary concrete (from two strikes to six strikes in experimental tests).
- FE-model predicted failure for plain concrete to occur in two strikes which is the same to the experimental results.
- Failure in PPLWAC FE-model and experimental tests took place in four and six strikes, respectively. The difference between experimental and numerical results could be caused by the existing difference between real material properties and the one used as input data for PPLWAC concrete in defining Equation of State (EOS) and the yield surface.
- In both FE-model and experiments, tensile failure was the dominant failure pattern for plain and PPLWACs. Also, crippling was generated in both plain and PPLWACs numerical results, spite the fact that it was not observed in plain concrete specimen.
- The results obtained from the finite element analysis are in fairly good agreement with the test results, and the soil-concrete material model is an appropriate material model to simulate both plain and fiber concretes. Further studies are, however, necessary to obtain real mechanical properties of PPLWAC concrete.

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