

MECHANICAL PROPERTIES OF LIGHTWEIGHT CONCRETE MADE WITH FIBER  
REINFORCED FLY ASH PELLETS

by

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## **ABSTRACT**

### **MECHANICAL PROPERTIES OF LIGHTWEIGHT CONCRETE MADE WITH FIBER REINFORCED FLY ASH PELLETS**

In this study, an extended experimental programme was conducted to investigate some physical and mechanical properties of lightweight concretes (LWCs) made with cold bonded fiber reinforced fly ash pellets and also tire chips as coarse aggregates. Crumb rubber and polypropylene fiber were used to reinforce the fly ash pellets. Lightweight concretes were investigated in two groups, namely lightweight aggregate concrete (LWAC) and lightweight rubberized concrete (LWRC) that contained both LWA and tire chips. Totally, 17 lightweight concrete (LWC) mixtures were produced with lightweight aggregates (LC, L1P, L5P and L1F) and tire chips at 0.40 w/c ratio and tested for mechanical properties such as compressive and splitting tensile strength, modulus of elasticity and so on. The findings of the study revealed that the compressive strength values of all LWAC series conformed to the limitation for structural use. The use of LWA and tire chips in concrete mixtures had negative effect on the basic engineering properties compared to the full use of crushed stone as coarse aggregate. The strength loss of LWAC and LWRC can be accounted firstly for the weakness of lightweight fly ash aggregate compared to the mortar phase and normalweight coarse aggregate and secondly for the adherence problem existing between tire chips and matrix zone of lightweight concrete with cold bonded pellets and for the extra void entrapped by tire chips, respectively. However, bond strength increased with no trend when LWA and crushed stone were used together in an equal part as coarse aggregate by volume. This positive contribution of LWAs may be accounted for a better coherence and interlocking of the LWA with the surrounding concrete those minimize the cracking and so utilize the adhesion between the concrete and rebar. When the concrete series with full use of different LWAs as coarse aggregates are compared to each other, it is seen that average flexural strength, failure impact energy and fracture toughness of L1F(4-16) type concrete series were the highest that may be attributed to the extra adherence between polypropylene fiber reinforced pellets and matrix phase by the help of polypropylene fibers existing on the surface of aggregates. Besides, the use of tire chips with LWA in an equal part of coarse aggregate by volume had a positive effect to increase toughness due to energy absorbing capacity.

## ÖZET

### LİF KATKILI UÇUCU KÜL AGREGALARINDAN ÜRETİLMİŞ HAFİF BETONLARIN MEKANİK ÖZELLİKLERİ

Bu çalışma kapsamında, soğuk bağlama yöntemiyle üretilmiş lif katkılı uçucu kül toprakları ve lastik kırıntıları ile üretilmiş hafif betonların bazı fiziksel ve mekanik özellikleri incelenmiştir. Uçucu kül toprakları ince lastik kırıntıları ve polipropilen lifler ile üretilmiştir. Hafif betonlar, hafif agrega betonları ve hem hafif agrega hem de lastik kırıntısı içeren hafif lastikli betonlar olmak üzere iki grupta incelenmiştir. LC, L1P, L5P ve L1F hafif agregaları ile plastik kırıntıları içeren 17 hafif beton serisi 0.40 su/çimento oranı ile üretilmiş olup, basınç ve yarmada çekme dayanımı ve elastisite modülü gibi mekanik özelliklerinin tayini için test edilmişlerdir. Deneylerin sonuçları hafif agrega betonlarının basınç dayanım değerlerinin yapılar da kullanım açısından standartlara uygun olduğunu göstermiştir. Hafif agregaların ve plastik kırıntısının iri agrega yerine beton karışımlarında kullanımı normal betonlara kıyasla temel mühendislik özellikleri üzerinde olumsuz etkiye sebep olmuştur. Hafif agrega betonlarının dayanım kaybı uçucu kül hafif agregalarının beton harcı ve doğal iri agregalara göre daha zayıf olmasıyla, hafif lastikli betonların dayanım kaybı ise plastik kırıntıları ile harç arasındaki tutunma problem ve plastik kırıntılarının havayı tutma ve boşluğa sebep olma özellikleriyle açıklanabilir. Bunun aksine, donatı tutunma dayanımı hafif agrega ve kırma taş birlikte ve eşit hacimde kullanıldıklarında keskin bir trend göstermeksizin artmıştır. Bu pozitif katkı, hafif agregaların kendilerini çevreleyen beton harcı ile daha iyi tutunma ve kenetlenmeleri ve dolayısıyla çatlak oluşumunu minimize etmesine dayandırılabilir. İri agrega olarak tamamen hafif agregaların kullanıldığı beton serileri birbirleriyle kıyaslandığında, polipropilen lif ile güçlendirilmiş hafif agregalı olan beton serisinin (L1F(4-16)) diğerlerine göre eğilme ve darbe dayanımı ile kırılma tokluğu değerlerinin daha yüksek olduğu gözlemlenmiştir. Agregaların yüzeyinde bulunan polipropilen liflerin sağladığı ekstra tutunma yeteneğinin dayanım özelliklerini artırdığı söylenebilir. Ayrıca, plastik kırıntı ve hafif agregaların birlikte ve eşit hacimde iri agrega olarak kullanımı, iri agrega olarak tamamıyla hafif agregaların kullanımına göre kırılma tokluğunu plastik kırıntıların betonun enerji soğurma kapasitesini yükseltmesine bağlı olarak artırmıştır.

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## LIST OF SYMBOLS

A	air content (percentage of voids) in concrete
b	width of beam
D	density of concrete
D	diameter of the disc
D	diameter of the reinforcement bar
D	particle diameter
$F_c$	cohesive force applied during capillary state
g	gravitational acceleration
H	height to fall
h	thickness of beam
L	bond length
L	support span
m	mass of a single pellet
m	mass of the hammer
M	total mass of all materials batched
$M_c$	mass of the measure filled with concrete
$M_m$	mass of the measure
$n_{cr}$	critical revolution per minute
P	bending load
P	failure load
$P_{max}$	ultimate pullout load
R	radius of the disc
$R_0$	average radius value
t	time taken by the hammer to fall
U	impact energy per blow of the hammer
V	total absolute volume of the ingredients in the batch
V	velocity of the hammer at impact moment
$V_m$	volume of the measure
w	centrifugal acceleration

$w$	the weight of hammer
$X$	distance between loading points
$\alpha$	inclination angle of pelletizer disc
$\beta$	angle of the disc to horizontal plane
$\beta$	meniscus angle between particle and the liquid binder
$\varepsilon$	porosity of a pellet
$\mu$	coefficient of friction between pellet and the disc
$\sigma$	crushing strength of a pellet
$\sigma$	stress at mid-span
$\sigma$	surface tension of liquid
$\sigma_t$	tensile stress
$\tau_u$	ultimate bond strength

## LIST OF ACRONYMS/ABBREVIATIONS

AASHTO	American Association of State Highway and Transportation Officials
ACI	American Concrete Institute
ACV	Aggregate Crushing Test Value
ASTM	American Society for Testing and Materials
BS	British Standard
L1F	Lightweight Aggregate Reinforced by 0.1% Polypropylene Fiber
L1P	Lightweight Aggregate Reinforced by 0.1% Crumb Rubber
L2F	Lightweight Aggregate Reinforced by 0.2% Polypropylene Fiber
L2P	Lightweight Aggregate Reinforced by 0.2% Crumb Rubber
L3P	Lightweight Aggregate Reinforced by 0.3% Crumb Rubber
L5P	Lightweight Aggregate Reinforced by 0.5% Crumb Rubber
LC	Plain/Control Lightweight Aggregate
LVDTs	Linear Variable Differential Transformers
LWA	Lightweight Aggregate
LWAC	Lightweight Aggregate Concrete
LWACs	Lightweight Aggregate Concretes
LWAs	Lightweight Aggregates
LWC	Lightweight Concrete
LWCs	Lightweight Concretes
LWRC	Lightweight Rubberized Concrete
NLWAs	Natural Lightweight Aggregates
NWC	Normalweight Concrete
PP	Polypropylene
rpm	rotation per minute
SP	Superplasticizer
TC	Tire Chips

## 1. INTRODUCTION

In today's world, one of the most important challenges to the construction industry is to build more sustainable and environment friendly structures and infrastructures. For that reason, many researchers have tried to find valuable applications and technical uses on either naturally occurring materials such as clay, shale, slate, perlite and vermiculite or on industrial by-products, like fly ash, blast furnace slag, silica fume, industrial waste, etc. in construction of backfills and embankments, subbase and pavement base practices for subgrade stabilization, production of pozzolanic cement, cement replacement in concrete, brick and block manufacturing, lightweight aggregates and concrete production and so on [1-5]. For instance, the large scale utilization of fly ash for producing artificial lightweight aggregates (by sintering and cold bonding process), which have been practiced in many countries, is reducing rapid use of natural aggregates in the construction industry and so avoiding the country side, river beds and beaches from damaging activities of aggregate mining. Besides, this is providing a remarkable reduction of the emission of green house gases by reducing the need of large amount of cement whose production is a contributor to CO<sub>2</sub> emission, meaning an effective recyclable disposal of the fly ash and environment friendly source [6-10].

Recently, with respect to the fact that using lightweight aggregate concrete provides reduction in the dead load of the construction by decreasing the cross section area of beams, columns, plates and foundations and finally possible reduction in the use of steel reinforcement, which affect the construction from both simplification and economic aspects, more attention has been paid to the development of lightweight aggregate concrete [11-16]. Reduction of the construction dead weight induces to both having more span length of bridges (e.g. high performance lightweight floating bridges like in Norway) and taller buildings and even decreasing the risk of earthquake damages because the earthquake forces that will effect structures have a direct proportion to the mass of constructions [6, 17]. Besides, using lightweight concrete provides higher strength/weight ratio, better tensile strength capacity, superior heat and sound isolation characteristics owing to air voids existing in the lightweight aggregate [12, 18, 19]. On the other hand, high permeability of the lightweight concrete causes water absorption and access of harmful

substances into the concrete so that deterioration of concrete and corrosion of reinforcing steel by means of chloride penetration [17, 19].

Structural lightweight aggregate concrete is usually defined to have oven-dry density of 1680-1920 kg/m<sup>3</sup> by the specification of ACI 213R-03 [20]. In practice any LWAC (natural or artificial) that has an oven-dry density less than 2000 kg/m<sup>3</sup> can be considered as LWAC.

Since the main component of lightweight aggregate concrete is the aggregate and there are variations on production conditions and the materials which used to produce lightweight aggregates, it is significant to provide sufficient information on the characteristics and behavior of the lightweight aggregates. The use of lightweight aggregates (regarding volume fraction) with lower strength and elastic modulus than mortar matrix is significant to determine mechanical properties of the lightweight aggregate concrete [13, 21].

In addition to lightweight aggregate concrete, rubberized concrete is an alternative way to utilize waste materials such as tire rubber as fine and coarse aggregate. The disposal of waste tires in landfill is a serious environmental issue all around the world because the waste rubber is not easily biodegradable and landfills are limited especially in some countries. Therefore, waste tires have been used in the field of subgrade stabilization and insulation, road embankment and reproducing plastic products like drainage materials [22-24]. From this point of view, since cement mortar and concrete are the most important and the basic materials for construction industry throughout the world, it has been recommended to use waste tires as a construction material especially as fine aggregates in concrete [25-28].

According to the results of experiments, rubberized concrete is beneficial for civil engineering applications in terms of having high strain under impact effects due to high energy absorbing capacity (high impact resistance), low density and better sound isolation and exhibiting ductile fracture (non brittle failure) under compression and tension, although adding tire rubber particles as aggregates into concrete has resulted in remarkable decrease in mechanical properties such as compressive and splitting tensile strength and

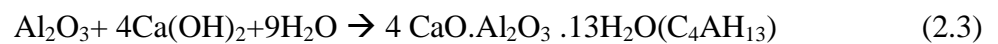
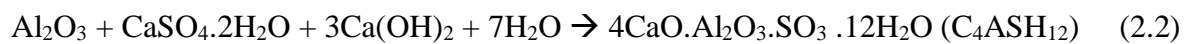
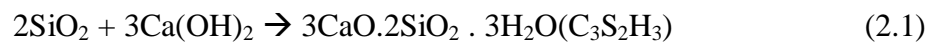
flexural strength. The strength loss of concrete was attributed to the lack of adhesion between rubber particles and cement paste by Khatip and Bayomy [29]. For instance, rubberized concrete is strongly recommended for highway barriers, airport runway and buildings on earthquake zone by the reason of having high energy absorbing capacity (toughness) and so decrease in damages possible to occur [30-32]. With the studies conducted by Gesoglu and Güneyisi [33, 34] increase in chloride penetration and water absorption was observed in rubberized concrete when the crumb rubber content increased.

In this study, an extended experimental laboratory programme was conducted with the scope of studying the effects of adding polypropylene fiber and crumb rubber into the artificial lightweight fly ash aggregates which were produced by way of cold bonding process and the mechanical properties such as compressive strength, modulus of elasticity, splitting tensile strength, impact resistance, bond developed reinforcing bar and flexural strength and toughness of structural lightweight concretes which consist of mentioned aggregates and tire chips in different mixes were investigated.

## 2. LITERATURE REVIEW

### 2.1. Fly Ash

Fly ash is a siliceous and aluminous pozzolanic material that, in the presence of water, will combine with an activator such as lime, kiln dust and free calcium hydroxide of hydration reaction of Portland cement to produce a cementitious material as follows:



It is important to point out that the pozzolanic reaction of fly ash occurs in a noticeable duration of delay as one or two weeks and it is much slower than hydration reaction of Portland cement [35]. The majority of fly ash particles are spherical in shape and range from 1  $\mu\text{m}$  to 100  $\mu\text{m}$  mostly bigger than 45  $\mu\text{m}$  with a specific surface area or fineness, between 2500 and 6000  $\text{cm}^2/\text{g}$  [36].

#### 2.1.1. Identification of Fly Ash

Fly ash is one of the residues generated in the combustion of coal. Fly ash is generally captured from the chimneys of coal-fired power plants, and is one of two types of ash that jointly are known as coal ash; the other, bottom ash, is removed from the bottom of coal furnaces. Depending upon the source and makeup of the coal being burned, the components of fly ash vary considerably, but all fly ash includes substantial amount of silicon dioxide ( $\text{SiO}_2$ ) (both amorphous and crystalline) and calcium oxide ( $\text{CaO}$ ). Toxic constituents include arsenic, beryllium, boron, cadmium, chromium, thallium VI, cobalt, lead, manganese, mercury, molybdenum, selenium, strontium, thallium, and vanadium, along with dioxins compounds. In the past, fly ash was generally released into the atmosphere, but pollution control equipment mandated in recent decades now requires that it has to be captured prior to release. In addition to economic and ecological benefits, the use of fly ash in concrete improves its workability, reduces segregation, bleeding, heat

evolution and permeability, inhibits alkali-aggregate reaction, and enhances sulfate resistance. Even though the use of fly ash in concrete has increased in the last 20 years, less than 20% of the fly ash collected was used in the cement and concrete industries [37].

### 2.1.2. Classifications and Specifications of Fly Ash

Two major classes of fly ash are specified in ASTM C 618 on the basis of their chemical composition resulting from the type of coal burned; these are designated Class F and Class C. Class F is fly ash normally produced from burning anthracite or bituminous coal, and Class C is normally produced from the burning of subbituminous coal and lignite (as are found in some of the western states of the United States). Figures 2.1 and 2.2 illustrate class C and F of fly ash. Class C fly ash usually has cementitious properties in addition to pozzolanic properties due to free lime, whereas Class F is rarely cementitious when mixed with water alone [6].

$$\text{Class F contains } \text{SiO}_2 + \text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3 > 70\% \quad (2.4)$$

$$\text{Class C contains } \text{SiO}_2 + \text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3 > 50\% \quad (2.5)$$

Fly ash which is produced at base loaded electric generating plants is usually very uniform. Base loaded plants are those plants which operate continuously. The only exception to uniformity is in the start-up and the shut-down of these plants. Contamination may occur from using other fuels to start the plant, and inconsistencies in carbon content occur until the plant reaches full operating efficiency. The ash produced from the start-up and shut-down must be separated from what is produced when the plant is running efficiently. In addition, when sources of coal are changed, it is necessary to separate the two types of fly ashes. Peak load plants are subjected to many start-up and shut-down cycles. Because of this, these plants may not produce much uniform fly ash.

The most-often-used specifications for fly ash are ASTM C 618 and AASHTO M 295. While some differences exist, these two specifications are essentially equivalent. The general classification of fly ash by the type of coal burned does not adequately define the type of behavior to be expected when the materials are used in concrete.

There are also wide differences in characteristics within each class. Despite the reference in ASTM C 618 to the classes of coal from which Class F and Class C fly ashes are derived, there was no requirement that a given class of fly ash must come from a specific type of coal. For example, Class F ash can be produced from coals that are not bituminous and bituminous coals can produce ash that is not Class F. It should be noted that current standards contain numerous physical and chemical requirements that do not serve a useful purpose. Whereas some requirements are needed for ensuring batch-to-batch uniformity, many are unnecessary [6, 35, 38].



Figure 2.1. Class C fly ash.



Figure 2.2. Class F fly ash.

### **2.1.3. Utilization Areas of Fly Ash**

For the sake of utilization of waste coal fly ash, many researchers have tried to find valuable applications and high technical uses such as in construction of backfills and embankments, subbase and pavement base practices for soil and subgrade stabilization, production of pozzolanic cement, cement replacement in concrete, brick and block manufacturing, lightweight aggregates and concrete production and so on [1, 3-5]. The large scale utilization of fly ash for producing artificial lightweight aggregates (by sintering and cold bonding) which have been practiced in many countries, reducing rapid use of natural aggregates in the construction industry, meaning an environment friendly source [8, 39-41].

## **2.2. Lightweight Aggregates**

LWAs can be divided into two groups namely natural LWAs and artificial LWAs in terms of originating from natural sources or being man-made, respectively. The use of lightweight aggregate in concrete has many advantages [7, 38, 42] including followings:

- Reductions in the sizes of column, beam and slab dimensions that result in larger space availability and reduction of dead load that also result in lighter and smaller upper structure. Thereby, reduction in cement quantity and possible reduction in reinforcement.
- A significant factor for high rise buildings (by reduction of dead load)
- Lighter and smaller precast elements needing smaller and less expensive handling and transporting equipment.
- Longer spans
- Improved cyclic loading structural response
- Greater design flexibility and lower cost
- High thermal isolation
- Advanced fire resistance

Furthermore, use of industrial by-products to produce artificial LWA for concrete has some other benefits in terms of community and the environment. Among these advantages are the following [7, 43, 44]:

- Effective recyclable disposal of the fly ash
- Helping to preserve natural and sometimes scarce materials of aggregates
- Avoiding the country side, river beds and beaches from damaging activities of aggregate mining
- Providing a remarkable reduction of the emission of green house gases by reducing the need of large amount of cement whose production is a contributor to CO<sub>2</sub> emission
- Establishing an industry with export potential especially to countries where natural aggregates are scarce or depleted

### **2.2.1. Natural Lightweight Aggregates (NLWAs)**

In general, natural LWAs occur with the specific physical and chemical events on melted lava following volcanic eruptions. When the molten lava gets in contact with air, it cools down and freezes to a highly amorphous and spongy porous structural mass. The most known volcanic natural LWAs are volcanic slags, tuffs, pumice and pozzolanas. They are different in void structure, color, shape and density. They have low density due to the presence of gas bubbles in the melted lava compare with the natural aggregates; however they are strong enough to be used to produce LWC. Apart from these volcanic natural LWAs, the use of air-dried fine particles of palm oil shells as aggregates of agricultural waste has also practical and economical benefits, especially in countries such as Malaysia, Indonesia and Nigeria where the palm oil industry is developed [45].

### **2.2.2. Artificial Lightweight Aggregates**

Artificial LWAs are produced by thermal treatment of materials which have expansive properties and by cold bonding agglomeration process in which bonding occurs with a chemical reaction between lime and pozzolanic particles of a material as fly ash. Thermal treatment is applied on either naturally occurring materials such as clay, shale,

slate, perlite and vermiculite or on industrial by-products, like fly ash, blast furnace slag, silica fume, industrial waste, sludge, etc.

### **2.2.3. Lightweight Aggregate Production with Fly Ash**

For the production of fly ash lightweight aggregate, there are three methods generally used; sintering, cold bonding and autoclaving (hydrothermal treating; steam curing for hardening of fly ash pellets) [5, 45-51]. Cold bonding as a method of lightweight aggregate production is considered to be more economical than sintering. Because sintering is an energy intensive process while cold bonding is a type of matrix bonding which provides energy saving. However, cold bonding depends on ability of pozzolanic reactivity of fly ash with calcium hydroxide at room temperature to form as pellets. Besides, cold bonding results in lower strength aggregates compared to sintering.

In this study cold bonding method was applied to produce fly ash lightweight aggregate.

2.2.3.1. Sintering Method. The term sintering process refers to hardening the pellets by gathering the fly ash particles together at the points of mutual contact. This process of sintered fly ash aggregates consists of two main operations. The first one involves pelletization of the fly ash-clay mixture by spraying water in a pelletiser disc. Then the thermal treatment applies to the mixture of pelletized fly ash aggregates and coal moving on sinter strand in order to be sintered by means of burning the coal with special units of a kiln like furnace hood which plays the role of a heat source. In the burning process the temperature should be in the range of 1050 to 1250°C. The whole mentioned process simply illustrated as in Figure 2.3.

The numbered equipment shown in the Figure 2.3 are followings: (1) Pan mill (2) Vibrating screen (3) Bucket elevator (4) Silo for coal (5) Silo for clay (6) Silo for fly ash (7) Belt conveyor (8) Pneumatic conveyor (9) Ribbon mixer (10) Bucket elevator (11) Water sprayer (12) Pelletizer (13) Furnace hood (14) Sinter strand/sintering belt (15) Strand draught fan (16) Chimney (17) Belt conveyor (18) Jaw crusher (19) Size grader (20) Finished product.

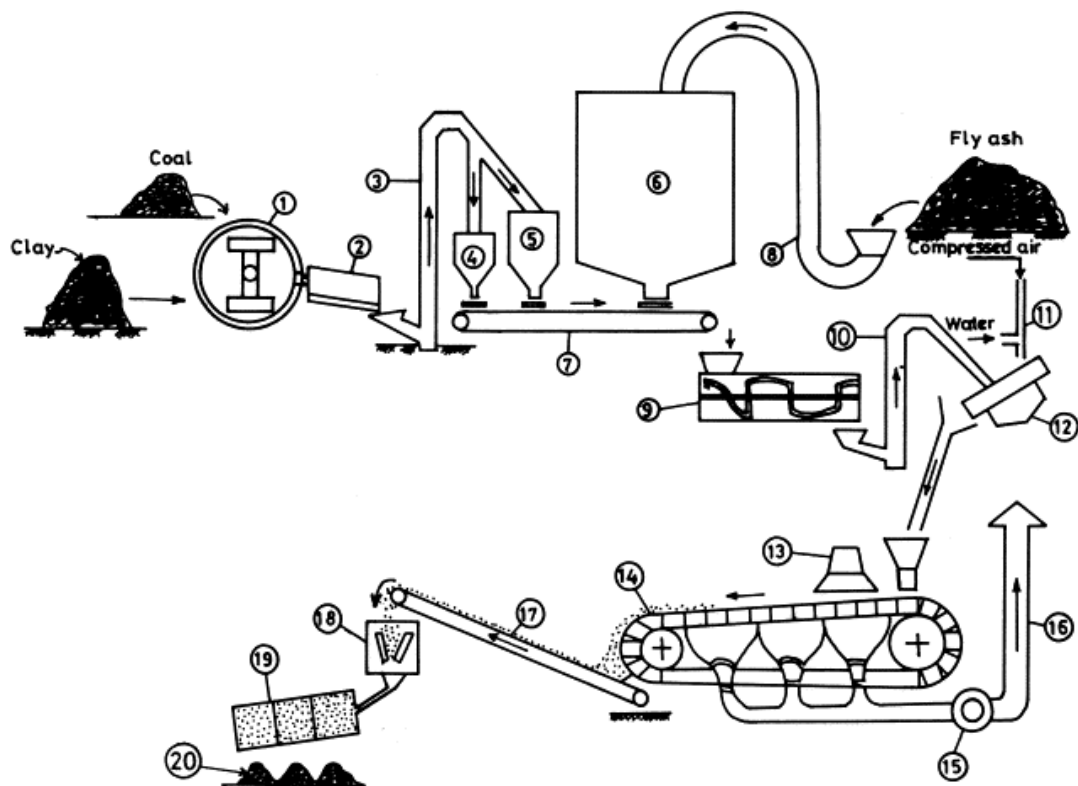


Figure 2.3. Schematic representation for production of sintered fly ash aggregates.

**2.2.3.2. Cold Bonding.** In general, cold bonding is a process in which any cementitious materials such as lime, cement, clay, shale etc. are mixed with fly ash. First of all, the fly ash and chosen cementitious material mixture are transported towards a pelletizer disc where water is sprayed on the mixture and circle shaped pellets are formed during the rotation of pelletizer pan with predetermined inclination angle and speed. In this process bonding is obtained by the chemical reactions between cementitious materials and fly ash particles due to the ability of pozzolanic reaction of fly ash. As a result of this reaction calcium silicate hydrates which are the main elements providing strength of the matrix, are produced.

#### 2.2.4. Physical Properties of Lightweight Aggregates

Physical properties of lightweight aggregates such as specific gravity, unit weight, water absorption of different fine materials such as sewage sludge ash, fly ash, silica fume,

zeolitic tuff, clay, slate, perlite etc. were investigated and compared by many researchers. In experimental studies the sintering temperatures mostly differed from 1000 to 1300 °C.

In general the heat and polymer treatments decreased porosity [39]. By transformation of the crystalline products to glassy ones, the density of the solids had a trend of reduction with increasing temperature of heat treatment. Besides, when rapid cooling is compared to slow cooling, solid density resulted in a lower value for equal temperature levels of heat treatment, 1300 °C. The density of polymer treated aggregate is lower than the non-treated original one because the density of polymer itself is less than the organic material of fry mixture.

According to a study on sintered fly ash aggregates reported by Li-xiong *et al.* [52] fresh pellets were dried at a temperature of 140 °C for 4 hours before pre-sintering process that included 700°C temperature for 25 minutes. Finally, pellets were sintered at temperature varied from 1200°C to 1250 degrees for 35 min and then evacuated from high temperature furnace. The lightweight aggregate showed 7.8 MPa strength and relatively lower water absorption of 4.2 per cent with a density of 843 kg/m<sup>3</sup>.

A research was conducted on coal fly ash samples of a thermal power plant to examine the sintering behavior of fly ashes with no organic binders [53]. For instance, one of the fly ash samples color changed from light to dark grey with a smooth surface after heat treatment at the temperature of 1175 °C. And the others also were prone to change in color and surface texture with the heat treatment process. As a result of porosity the sintered samples had relatively lower density varied between 2.43–2.58 g/cm<sup>3</sup> and high water absorption.

The ability to sinter of a class F fly ash was examined as a function of sintering temperature in the range of 1050-1200°C and time from 0 to 90 min [36]. For each applied temperature, when the sintering time increased, also the density generally raised. However, the optimum density increase was seen at 1100 °C with 60 minutes sintering. In the case of 1200 °C and 90 minutes of sintering time a maximum density of 1708 kg/m<sup>3</sup> was obtained. Bulk density and water absorption are indirectly proportional, the greater the density, the lower should be the water absorption.

Kockal and Ozturan [47] investigated physical characteristics of lightweight fly ash aggregates with different binders (bentonite and glass powder) produced by heat treatments of 1100, 1150 and 1200 °C. Specific gravity, water absorption and porosity of pellets which produced with both only fly ash and the mixture added different amounts of binders to fly ash, were measured after heat treatments. The use of binders (regardless of binder type) caused to a significant reduction in specific gravity of all lightweight aggregates sintered at the highest temperature, 1200°C owing to expansion. However, at relatively low sintering temperatures of 1100 and 1150°C, adding binders to fly ash increased the specific gravity due to higher specific gravity of the binders compared to fly ash. Specific gravity of lightweight aggregates produced by using only fly ash increased constantly with incremental sintering temperature can be accounted for the intensive glass formation with discontinuous and small size pores at higher temperatures as also reported by Al-Bahar and Bogahawatta [54]. Water absorption of all lightweight aggregates reduced with increasing temperature. Relatively high water absorption was obtained at 1100 °C due to open and connected porosity of the pellets. Although lightweight aggregates had lower water absorption at 1150 °C due to discontinuous porosity and small pore size, further decrease in water absorption was obtained at 1200 °C owing to closed and disconnected porosity. The reduction of water absorption at the same temperature was also reported [55, 56] to be attributed to the glassy texture formation on the surface of the aggregates. Besides, increasing of binder content regardless of binder type resulted in a decrease of water absorption as reported by Ramamurthy and Harikrishnan [57]. In general, total porosity decreased with the increase in sintering temperature for all types of aggregates.

On the other hand, Geetha and Ramamurthy [58] conducted a study on the properties of *cold-bonded* aggregate such as bulk density, porosity and water absorption. An increase in binder raised the strength and decreased the open porosity thereby lowering the water absorption. After curing period, bulk density of aggregates was measured and obtained in the range of 750-980 kg/m<sup>3</sup> that is lower than bulk density of normalweight aggregates. This is accounted for the specific gravity of the raw materials and the presence of porosity in aggregate particles. The bulk density rose with binder dosage with respect to the pozzolanic reaction between fine and binder materials that lead to form more hydration products ending up with dense structure with less open porosity thereby reducing the water absorption. The ability to filling up the pores of fine material (fly ash) was another

contribution. The porosity reduced by increasing the binder dosage from 44.2% to 32% and 35% with cement and with lime, respectively.

Baykal and Döven [5] examined the effects of different binders (8% cement and lime by weight of fly ash) adding to fly ash on physical properties of cold-bonded lightweight aggregates. When pellets were produced with binders, the unit weight measured with increment between 2 and 8 per cent by adding cement or lime to fly ash. Besides, addition of binders increased the specific gravity values of aggregates and decreased the porosity and water absorption. The specific gravity increased by 3–4% and water absorption decreased by 4–9% respectively by the help of lime and cement addition, regarding to average values of fly ash pellets with no additives.

According to the study conducted by Gesoglu *et. al* [59] the specific gravity values of cold-bonded lightweight aggregates were obtained in the range of 1.72 and 1.80 with respect to be produced by different fly ash in physical and chemical properties and treated with water-glass and slurry. For a specific group of lightweight aggregates mentioned while water absorption was 27% by weight, it decreased to 3.0 and 18% by water glass and slurry treatment, respectively.

The permeability of cold-bonded fly ash lightweight aggregates was greater when compared to normalweight aggregates and sintered lightweight aggregates and so was the water absorption [60].

#### **2.2.5. Mechanical Properties of Lightweight Aggregates**

While the strength of natural coarse aggregate can be achieved experimentally by testing the base rock, it is difficult to do that for artificial lightweight aggregates by the same way. Hence, indirect tests such as the Los Angeles abrasion test, aggregate crushing value test-ACV and 10 % fines value test are used to evaluate the strength of lightweight pellets as defined by ASTM C 131, BS 812-110 and BS 812-111, respectively. Apart from these, Equation 2.6 was utilized to calculate the strength values of pellets;

$$\sigma = \frac{2.8 * P}{\pi * X^2} \quad (2.6)$$

where, P is the failure load and X is the distance between loading points [47, 61-64].

Nilsen *et al.* [65] suggested that the theory of granular mechanics and the energy dissipation due to a stress cycle can be used to estimate the compressive strength and to assess the quality of lightweight pellets. Yang and Huang [21] proposed a numerical approach to predict the compressive strength of lightweight coarse aggregate particles with a micromechanics method by observing the trend of strength variation for different volume fractions of pellets. In addition to this, a method for predicting the strength of cold-bonded fly ash aggregates was developed by Tangtermsirikul and Wijeyewickrema [66]. With respect to this method they proposed an equation for calculating tensile stress at failure plane as shown in Figure 2.4 to represent the tensile strength of fly ash aggregates. The general formula for calculation of tensile stress was given by the following expression;

$$\sigma_t = \frac{2 * P}{R_0^2} \quad (2.7)$$

where,  $\sigma_t$  refers to the tensile stress at the time of crushing at center of tensile failure plane (MPa), P stands for the point load at the time of pellet breaking (N),  $R_0$  is the average radius value calculated from three measurements in three normal directions of the fly ash pellet (mm).

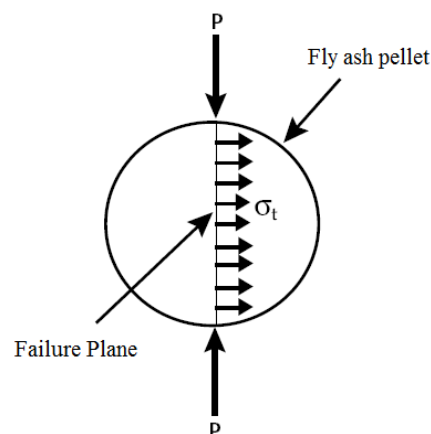


Figure 2.4. Loading position and tensile stress distribution at failure plane.

In order to estimate the mechanical quality of the aggregates, Wasserman and Bentur [39] utilized the crushing strength values of lightweight aggregates. The crushing strength value was calculated as the ratio between the load and the cross section area of the cylinder that was filled up with lightweight aggregates to be pressed.

With respect to the study on different types of lightweight aggregates with clay and sludge, crushing strength, impact resistance and the abrasion loss of the lightweight aggregate reduced when the ratio of sludge to clay increased [56].

The aggregate (Lytag) were rapid cooled after sintering process at 1300 °C showed decrease in crushing strength as a result of surface cracks occurred due to the thermal gradients [39]. Although Lytag aggregates were sintered at 1250-1300 °C had lower porosity than the original one, they presented lower strength values contrary to the fact that lower the porosity greater the strength in general. This is because of various effects such as mineralogical change, cracks and internal defects stem from thermal gradients and stresses.

With the scope of study conducted by Kockal and Ozturan [47], the effects of binders and different heat treatments on physical properties and crushing strength of lightweight fly ash aggregates were investigated. Bentonite and glass powder were used as binders in different amounts. The lightweight pellets were sintered at temperatures of 1100, 1150 and 1200°C. While the strength of aggregates with no binder increased continuously by sintering at all mentioned temperatures (through densification of fly ash with no expansion), aggregates with binders (regardless of binder type) gained the highest strength at 1150°C. The strength gain was attributed to the dense structure with discontinuous and small size pores occurred at the temperatures lower than 1200°C. Expansion of pellets and mineralogical changes of the binders induced by melting at the temperature of 1200°C was pointed out to be the cause of decrease in strength of aggregates as claimed by previous studies [36, 61, 67-69].

Baykal and Döven [5] also examined the effects of different binders( %8 cement and lime by weight of fly ash) adding to fly ash on crushing strength of cold-bonded lightweight aggregates for 7, 14 and 28 days of curing time. The rate of strength gain and the strength value for the pellets with cement as a binder was higher until 14 days of curing

time. Aggregates with lime and cement had higher strength values than the aggregates made with fly ash only for all curing periods. Although strength values of pellets with cement higher than those of pellets with lime until 14 days of curing time, the situation was on the contrary for 28 days of curing time.

Gesoglu *et al.* [48] investigated the effects of fly ash properties on characteristics of cold-bonded fly ash lightweight aggregates. They used two types of fly ashes different in surface area and CaO content generally. Fly ash pellets were produced with no binders but surface treatment with water glass. The aggregates produced with a fly ash having higher specific surface and lower CaO content had higher strength than that of the aggregates produced with the second group of fly ash. However, when the second group fly ash aggregates surface treated by water glass, the strength of these aggregates increased remarkably. This is because water glass improves the hydration of cementitious materials with high CaO content by consuming CaO and penetrating into the aggregate hence healing the surface cracks. Besides, water glass reacts with  $\text{Ca(OH)}_2$  to produce C-S-H (tobermorite gel, main source of strength) as also reported by a previous study [70].

Mechanical quality of an aggregate particle such as crushing strength is affected by several interrelated factors such as density, pore size and distribution, water absorption, shape of aggregates (spherical shaped aggregates have higher strength values), surface cracks of pellets, bloating of the aggregates, melting point of binders and mineralogical change and densification effects due to sintering and thermal gradients [71, 72].

When the studies on mechanical properties of lightweight aggregates were generally examined, it can be concluded that the presence of fine particles of materials used to produce lightweight aggregates, water glass and slurry treatments of the pellets (decrease in porosity and so water absorption) and sintering process (reduction of open porosity that is the main reason of water absorption) (if does not cause to internal defects) are advantages for mechanical properties of LWA.

## **2.3. Pelletization Process**

### **2.3.1. Definition of the Pelletization Process**

Pelletization process is the agglomeration of moisturized fine particles such as dusts or powders which are consolidated into larger solid materials, such as pellets in a rotating pelletizer disc or drum without external force. The pellets formed attain strength by mechanical forces generated when pellets clash with each other and the wall of pelletizer disc during the process [5, 46, 73] The generated pellets are nearly spherical or slightly angular and vary in color depending on the properties of materials in dry mixes. The grain size distribution of spherical shaped pellets can be controlled by positioning scrapping blades through inner and outer path of pelletizer pan.

The pelletization phenomenon was first initiated by a Swedish researcher A.G.Anderson in 1912 while just a year later C.A.Brackelsberg, a German scientist, developed a similar balling process in 1913. In the mentioned decade, due to the necessity of sintering concentrated substances, further studies on this process especially in the United States showed improvement by addition of binder to the fines and thermal treatment of pellets at elevated temperatures. Later, E.P.Barret and S.R.Dean from U.S. Bureau of Mines investigated the properties of agglomerated fines sintered at 500°C, while a similar study was conducted by E.A.Davies in University of Minnesota by using same methodology. This process was not feasible from the financial aspect until 1950's when the first pelletization plant was established in Sweden with a capacity of 10 to 60 tones production per day. Besides, the world's first enormous plant with the capacity of approximately 6 million tons of yearly pellet production was founded in the U.S.A. [73].

### **2.3.2. Theory of Pelletization**

The pelletization and the strength of pellets produced are influenced by the properties of raw materials like grain size distribution and wetting capability of particles, moisture content in media and mechanical parameters, such as the rotation speed and angle of pelletizer disc or drum [5, 49].

Investigations and analysis applied to these parameters with respect to mechanic and kinetic laws formalized the theory of pelletization process. The main approaches of the theory are as follows [5, 73];

When a fine-grained material is wetted, a thin liquid film occurs on the surface of the grains, which forms connection between the grains like bridges as in Figure 2.4 a and b. In the event that the particles are rotated in a disc for some more time, ball shape structures with advanced bonding forces between grains are generated owing to gravitational and centrifugal forces (Figure 2.4 c and d).

The parameters of pelletization process and final magnitude of pressure occurred on the grains play important role on the strength of the pellets. Besides, magnitude of coherence of the pellets depends on capillary forces- $P$ , the surface tension originated by the height of liquid column. In another words, the capillary force is a function of meniscus angle ( $\beta$ ) between the particle and the liquid binder and particle diameter ( $D$ ) as illustrated in Figure 2.5. Mechanical and capillary forces are two main factors that constitute the coherence of the structure of the pellets.

The pelletization process can be categorized into three stages with respect to the degree of saturation of intergranular spaces with water as below;

- the pendular state, where the water is present at only the point of contacts of grains
- the funicular state, where, some of the vacant pores are completely filled with water compared to the pendular state
- the capillary state, where all intergranular spaces are completely filled with water however no water film exists on the surface of the pellet. This state is the most suitable and desired one for pellet formation, which provides the highest tension force generated by binder between the particles.

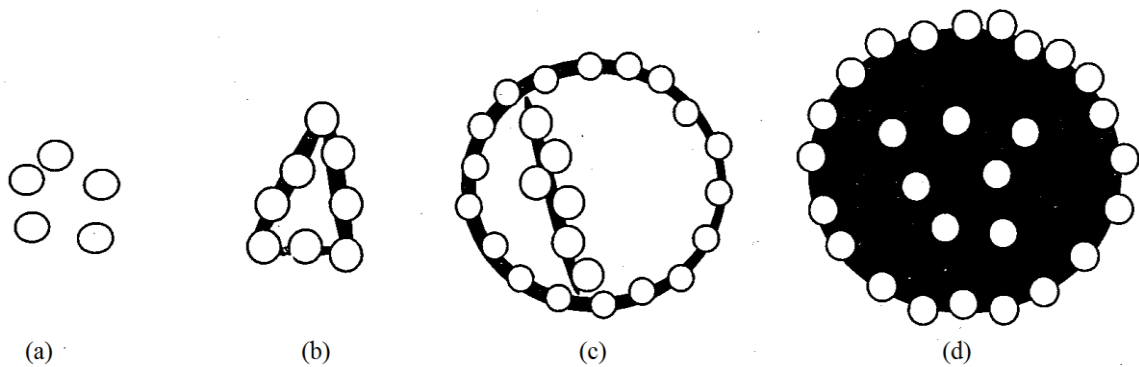


Figure 2.5. Mechanism of pellet formation [5].

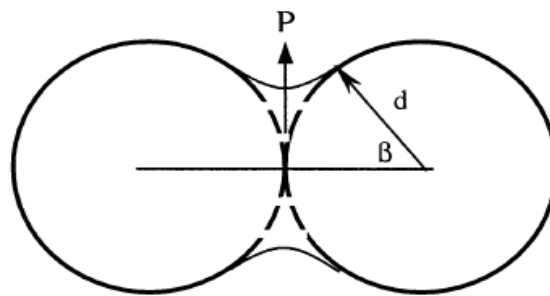


Figure 2.6. Configuration of surface tension force created by water bridge between two grains [5].

In order to formulize the capillary and cohesive forces exerted on the particles of fine material used for pelletization, necessary assumptions are accepted as followings:

- The particles of pellets are completely distributed
- All pellets are ball shaped with uniform diameters
- The uniform bonding available during the ball section

With respect to these assumptions, cohesive forces in the capillary state can be obtained by the Equation 2.7 as following;

$$F_c = 8 \times \frac{(1 - \varepsilon) \times \sigma}{\varepsilon \times D} \quad (2.8)$$

where,  $\sigma$  refers to the surface tension of the liquid,  $F_c$  is the cohesive force applied during capillary state,  $\varepsilon$  refers to the porosity of pellet and finally  $D$  is the diameter of ball shaped grains [5, 73].

According to the fact that mechanical parameters affecting the process of pelletization, it seems obvious that movement of the pellets in the pelletization disc should be defined regarding to rotation speed of the disc (Figure 2.6). For low rotation speed gravitational force determining the movement of pellets while for high speed centrifugal force governing the movement. Besides, the angle of pelletization disc to the horizontal plane and diameter of the disc are two factors for definition of the most suitable process for rotation speed of the disc in order to prevent dominancy gravitational or centrifugal forces. Figure 2.7 illustrates the forces acting on a single pellet during the pelletization process in a pelletization disc with radius 'R'.

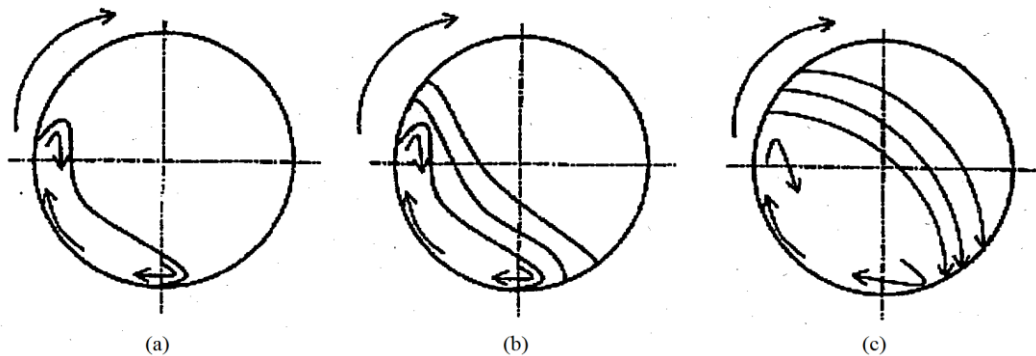


Figure 2.7. Movement of material rotating at different speeds in disc pelletizer[5].

The theoretical studies on these parameters lead to the following equations in terms of the 'critical revolutions per min'. The term 'critical' stands to define the state where the gravitational and centrifugal forces are in equilibrium on the disc's plane;

As the theoretical studies conducted on these parameters, following equations were obtained according to the concept 'critical revolutions per minute'. The term 'critical'

refers to the condition which gravitational and centrifugal forces are in balanced on the disc's plane as shown in Equation 2.9;

$$m * g * \sin \beta + \mu * m * g * \cos \beta = m * R * w^2 \quad (2.9)$$

where,  $m$  refers to the mass of a single pellet,  $g$  stands for gravitational acceleration,  $\beta$  is the angle of the disc's to horizontal plane in degrees unit,  $\mu$  refers to the coefficient of friction between the pellet and the disc,  $R$  is the radius of the disc,  $w$  is the centrifugal acceleration in radians/sec<sup>2</sup>.

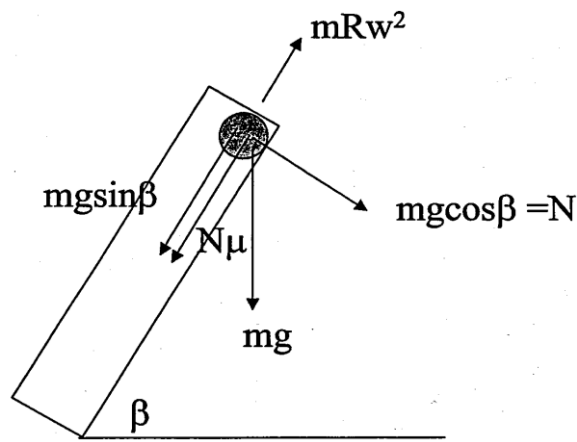


Figure 2.8. Forces applied to a single pellet during the process.

However, in case where centrifugal acceleration and gravitational forces are in balanced then the normal force applied by the pellet tend to become zero and hence Equation 2.9 simplifies into;

$$m * g * \sin \beta = m * R * w^2 \quad (2.10)$$

and then 'critical revolutions per minute' calculated by the formula below;

$$n_{cr} = \frac{42.3}{\sqrt{D}} \sqrt{\sin \alpha} \quad (2.11)$$

where,  $n_{cr}$  refers to the critical revolutions per minute (rpm),  $D$  is the diameter of the disc in meters and  $\alpha$  refers to inclination angle in degrees units.

## **2.4. Lightweight Concrete**

### **2.4.1. Lightweight Aggregate Concrete**

Recently, with respect to the fact that using lightweight aggregate concrete provides reduction in the dead load of the construction by decreasing the cross section area of beams, columns, plates and foundations and finally possible reduction in the use of steel reinforcement which affect the construction from both simplification and economic aspects, more attention has been paid to the development of lightweight aggregate concrete [11-13, 15, 19]. Reduction of the construction dead weight induces to both having more span length of bridges(e.g. high performance lightweight floating bridges like in Norway) and taller buildings and even decreasing the risk of earthquake damages because the earthquake forces that will affect structures have a direct proportion to the mass of constructions [6, 17]. Besides, using lightweight concrete provides higher strength/weight ratio, better tensile strength capacity, superior heat and sound isolation characteristics owing to air voids existed in the lightweight aggregate [12, 18, 19]. On the other hand, high permeability of the lightweight concrete causes water absorption and access of harmful substances into the concrete so that deterioration of concrete and corrosion of reinforcing steel by means of chloride penetration into the concrete [17, 19].

Since the main component of lightweight concrete is the aggregate, it is significant to provide sufficient information on the characteristics and behavior of the lightweight aggregates. The use of lightweight aggregates (regarding volume fraction) with lower strength and elastic modulus than mortar matrix is significant to determine the compressive strength and elastic modulus of lightweight aggregate concrete [13, 21].

There are a lot of variations on production conditions and the materials which used to produce lightweight aggregates. Thus, there is a wide range of properties of lightweight aggregates. Despite of this wide range, only the aggregates produced from fly ash, blast furnace slag, clay, shale, slate have adequate strength characteristics in order to be used for concrete productions.

According to the investigation reported by Zhang and Gjørsv [41], high strength lightweight aggregates different in particle shape, surface texture and pore structure are available in European markets. With respect to the fact that most of the pores in aggregates were open, the water absorption was under a question. Experiments showed that approximately more than half of water absorption within 24 hours occurred during the first 30 minutes. With the purpose of reduction of the water observation and increasing the lightweight aggregate strength, surface treatment is essential by the help of coating the pellets with water glass ( $\text{Na}_2\text{O} + \text{Si}_2\text{O}$ ), heating the surface (if pellets sintered above sintering temperature), submersing the aggregate particles in cement or silica fume slurry [4, 39].

With respect to the study of Zhang and Gjørsv [74], there was no efficient pozzolanic reactivity between cement paste and lightweight aggregates such as expanded clay and sintered fly ash. They pointed out that recrystallization of the mineral compounds are the main cause of the low degree of pozzolanic reactivity.

Lightweight concretes produced with a density range of nearly 300-2000  $\text{kg/m}^3$  with strength various from 1 to 60 MPa can be compared with normal weight concrete which has density with a range of 2100-2500  $\text{kg/m}^3$  and strength from 15 to more than 100 MPa [75].

Compressive strength of LWCs that were produced by using cold-bonded fly ash pellets was as high as 60 MPa. The order of compressive strength values of different LWCs were correlated with that of LWAs which used in each group of LWCs [48]. The use of LWAs at higher amounts deteriorated the mechanical properties of LWCs as reported by the previous studies [6, 76, 77].

Gesoglu *et al.* [76] examined the mechanical properties of LWC such as compressive strength, static elastic modulus and splitting tensile strength and obtained the values of those varied from 20.8, 14.2 and 1.86 to 47.3, 24.4 and 3.94, respectively. Addition of silica fume (increasing cementitious material) and decreasing the volume ratio of lightweight coarse aggregate gave rise all these mechanical properties. With respect to ACI limitation, density of fresh concretes yielded with relatively high value for LWCs ranged

from 1950 to 2170 kg/m<sup>3</sup>, spring from using high content of cement in the mixture of concrete and natural sand as fine aggregate as reported in previous studies [78].

With another research, compressive and splitting tensile strengths, and modulus of elasticity of lightweight concretes were investigated by Gesoglu *et al.* [59]. These concretes were produced with LWAs that were different in physical and chemical properties and also some groups of LWAs were water glass and slurry treated. LWCs produced with water glass treated LWAs gave rise higher value of these mechanical properties than those of the LWCs with slurry treated LWAs. Another group of LWCs which was not treated had the lowest values of mentioned properties.

Kockal and Ozturan [60] investigated the physical and mechanical properties of LWCs made with sintered lightweight fly ash aggregates that were produced with glass powder (LWGC) and bentonite (LWBC), and non-sintered cold-bonded fly ash aggregates (LWCC). Air content, slump and density values of fresh concretes; LWCC, LWBC, LWGC resulted in 3.9, 4.3, 4.1% and 15, 15.5, 16.5 cm and 1991, 1960, 1975 kg/m<sup>3</sup>, respectively. Besides, Compressive strength, splitting tensile strength and modulus of elasticity values of hardened concretes at the 28th day; LWCC, LWBC, LWGC resulted in 42.3, 53.5, 55.8 MPa and 3.7, 4.8, 4.9 MPa and 19.6, 26.0, 25.7 GPa, respectively.

#### **2.4.2. Lightweight Rubberized Concrete (LWRC)**

The disposal of waste tires in landfill is a serious environmental issue all around the world because the waste rubber is not easily biodegradable and landfills are limited especially in some countries. As another way to dispose waste tires, burning is the cheapest and the easiest way. However, it is considered to be the most hazardous reason of air pollution so prohibited by law in many countries [22, 23]. In the past few decades, a lot of studies have been conducted in regard to utilize waste tire rubbers. Some researchers proposed to mix waste tires with asphalt or bituminous materials and to use as fuel material and as raw materials of rubber goods [79]. Apart from these applications, waste tires have been used in the field of subgrade stabilization and insulation, road embankment and reproducing plastic products like drainage materials [24]. While these fields of applications contributing to consume and recycle waste tire rubber, the current volume of tires in

landfills is much more than consumption of scrap tires. From this point of view, since cement mortar and concrete are the most important and the basic materials for construction industry throughout the world, it has been recommended to use waste tires as a construction material especially as fine aggregates in concrete [25-28].

According to the results of experiments, the use of rubberized concrete in constructions that are subjected to the impact loading will be advantages owing to significant increase in toughness, thus impact resistance. For instance, rubberized concrete is strongly recommended for highway barriers, airport runway and buildings on earthquake zone by the reason of having high energy absorbing capacity (toughness) and so decrease in damages possible to occur [30-32].

According to the study of Savas *et al.* [80], utilization of scrap tires in concrete as aggregates, aggravates freeze-thaw resistance of concrete. With the studies conducted by Gesoglu and Güneyisi [33, 34] increase in chloride penetration, water sorptivity and water absorption was observed in rubberized concrete when the crumb rubber content increased.

As indicated in many researches rubberized concrete is beneficial for civil engineering applications in terms of having high strain under impact effects due to high energy absorbing capacity (high impact resistance), low density and better sound isolation and exhibiting ductile fracture (non brittle failure) under compression and tension, although adding tire rubber particles as aggregates into concrete has resulted in remarkable decrease in mechanical properties such as compressive and splitting tensile strength and flexural strength. The use of only coarse rubber particles (tire chips) affects these properties more negatively than do only fine particles (crumb rubber) [29, 79, 81, 82]. The strength loss of concrete was attributed to the lack of adhesion between rubber particles and cement paste by Khatip and Bayomy [29].

In order to minimize the strength loss of concrete, surface treatment of the rubber particles by the way of immersion in NAOH solution to increase adhesion to surrounding environment and adding fine mineral additives such as silica fume into the concrete mixture for better filling of the pores were recommended [82-84].

According to study of Güneyisi *et al.* [79] an increase in rubber content resulted in a decrease of slump and unit weight of rubberized concrete with or without silica fume. When w/c ratio was 0.60 without rubber and silica fume slump and unit weight of plain concrete were 19cm and 2400 kg/m<sup>3</sup> respectively. However, in the condition that rubber and silica fume were present at the ratio of 50 and 20% respectively with the same w/c ratio, slump was 0 and unit weight of rubberized concrete was 1800 kg/m<sup>3</sup>. Besides, when w/c ratio changed from 0.60 to 0.40 without rubber and silica fume, slump and unit weight of plain concrete were 15cm and 2430 kg/m<sup>3</sup> respectively. While rubber and silica fume were present at the ratio of 50 and 20% respectively with the new w/c ratio, slump was 0 and unit weight of rubberized concrete was 1830 kg/m<sup>3</sup>.

As reported by some researchers, density and compressive strength of concrete decreased remarkably and water absorption of concrete increased with rubber content because of porous structure and thus durability properties of rubberized concrete were affected negatively [33, 81, 85, 86].

Khatib and Bayomy [29] indicated that increase in rubber content ended up with a decrease of slump and workability of concrete. When rubber content increased to 40% as a percent of total aggregate volume, slump value dropped to zero. With respect to the further investigation, using only crumb rubber affected slump and workability of concrete worse than only tire chips.

Khaloo *et al.* [87] and Khatib and Bayomy [29] attributed the increasing air content of rubberized concrete to the tendency of rubber particles to entrap air and porous structure of interfacial zone between rubber particles and mortar matrix.

### **2.4.3. Mechanical Properties of Lightweight Concrete**

2.4.3.1. Compressive and Tensile Strength and Modulus of Elasticity. The compressive strength of structural lightweight concrete is high as density. The compressive strength of such concrete is directly proportional to density. An increase in compressive strength of concrete is occurred as a result of improvement on competitiveness of concrete structures. The strength of concrete is 75 MPa, density is 1940 kg/m<sup>3</sup> for hardened concrete. For

lightweight concrete bridges, the compressive strength requirement is 50-60 MPa [88]. Factors affecting compressive strength have also effect on tensile strength for lightweight aggregate concrete. However, the fracture path and water content differs in these concrete types. For lightweight aggregate, fracture path passes through body and water content is higher due to the formation of moisture gradients on absorption of water. On the other hand, fracture path passes around the circumference of aggregate and water content is lower [75]. Generally, E-modulus of lightweight aggregate concrete is nearly half of normal concretes with same strength [88]. In literature, it is seen that the strength of the aggregate is the primary factor that affects the strength of concrete. For lightweight aggregate, compressive strength of concrete increases, elastic modulus decreases and ultimate strain at peak load increased compared to normal weight concrete.

The effects of water curing on the strength of normalweight and lightweight concretes were investigated by using two structural lightweight concrete at 35 and 50 MPa and normalweight concrete with natural aggregates. For lightweight concrete, 7 days of initial curing and seaside exposure gives better strength development. On the other hand, continuous water curing gives best strength development for normal weight concrete [89, 90].

The effect of curing conditions on strength and elastic modulus of lightweight high strength concrete is investigated [91] in different conditions such as air curing, moist curing under polyethylene sheet, 100% moist curing and water curing at different temperatures and in different time scales as 7 days or 28 days. In general, water curing and moist curing under polyethylene sheet gives highest elastic modulus and compressive strength. However, the compressive strength and elastic modulus are directly proportional irrespective of curing conditions.

With respect to the study of Güneyisi *et al.* [79] an increase in rubber content concluded with a decrease of compressive and tensile strength and modulus of elasticity of rubberized concrete with or without silica fume. When w/c ratio was 0.60 without rubber and silica fume, mentioned mechanical properties of plain concrete were 53.8, 3.1 MPa and 33.1 GPa respectively. Nevertheless, in the condition that rubber and silica fume were available at the ratio of 50 and 20% respectively with the same w/c ratio, these mechanical

properties of rubberized concrete changed to 8.6, 0.8 MPa and 6.5 GPa respectively. Besides, when w/c ratio changed from 0.60 to 0.40 without rubber and silica fume compressive and tensile strength and modulus of elasticity of plain concrete increased to 75.8, 4.1 MPa and 45.9 GPa respectively. While rubber and silica fume were present at the ratio of 50 and 20% respectively with the new w/c ratio, mentioned mechanical properties of rubberized concrete gave rise to 11.7, 1.0 MPa and 8.2 GPa respectively.

As reported by the study of Eldin and Senoci [82] concrete with crumb rubber and tire chips presented lower compressive and splitting tensile strength in comparison with ordinary Portland cement concrete. When fine aggregate was totally replaced by crumb rubber, a decrease of 65% in compressive strength and approximately 50% in splitting tensile strength was observed. However, the situation was worse especially in compressive strength (85% reduction) when coarse aggregate was fully replaced with tire chips. On the other hand, specimens of both concretes exhibited ductile failure and high energy absorbing capacity meaning increase in flexural strength and high impact resistance of rubberized concrete.

Pelisser *et al.* [92] investigated the effects of tire rubber addition to concrete mixture on compressive strength and modulus of elasticity of concrete. For that reason they produced three types of concretes: ordinary Portland cement concrete, concrete with tire rubber and concrete with tire rubber modified by silica fume. In relation to the addition of tire rubber to concrete mixture, a considerable decrease in compressive strength and modulus of elasticity and so stiffness of rubberized concrete compared to reference concrete was obtained. However, by the help of silica fume modification of concrete that was produced with rubber, significant recovery for mentioned mechanical properties was observed.

According to the results of experiments conducted by Liu *et al.* [25], Khaloo *et al.* [87] and Turatsinze and Garros [93] drastic reduction in compressive strength and modulus of elasticity of concrete was observed with the increasing of rubber content in concrete mixture.

**2.4.3.2. Impact Resistance.** As investigated, there is not a research on impact resistance of LWAC. However, there are a few studies on impact resistance of rubberized concrete. In

this study, impact resistance (through failure energy and number of blows to crack) of LWC (with LWA and rubber) was determined by the methods which were used on plain and steel fiber reinforced concrete by the previous studies [94-96].

Topcu and Avcular [31] examined the effects of steel and rubber reinforcement of impact resistance of concrete. They found out that impact resistance of steel reinforced concrete was higher than rubberized concrete. Besides, due to incremental energy absorbing capacity and elasticity of rubberized concrete compared to plain concrete, impact resistance of rubberized concrete especially with thick rubber was also higher.

The use of tire rubber as aggregate with replacing ratio up to 10% in concrete ended up with significant enhancement in the impact resistance of concrete as a result of increasing energy absorbing capacity [25].

2.4.3.3. Steel-Concrete Bond in Lightweight Aggregate Concrete. Steel-concrete bond is a process consists of adhesion, friction and support of the ribs in deformed steel. Against the bond strength of mechanism, the steel is pulled out of the confining concrete matrix as concrete load increases. By adding load, adhesion mechanism is activated initially. Adhesion is pasting of microscopic interlock onto imperfections and a plausible chemical reaction between surfaces. Due to adhesion, there is no real slip however the observed slip is because of local deformation adjacent to steel surface. Other two mechanisms are friction and rib support. These two mechanisms activated when adhesion fails and relative movements commence between surfaces of concrete and steel. While adhesion fails, it is possible to observe significant slips or formation of cracks. However, reinforced concrete elements should avoid from bond slip exceeding adhesion. Otherwise, it will result in internal cracking of permanent deformations [97]. The knowledge about bond-slip behavior of reinforcement in lightweight aggregate concrete is very little. Certain types of aggregates may result in shear failure between tops of the ribs and high yield bars, reason for low failure stress. On the other hand, other aggregates will lead to higher bond stresses for lightweight concrete more than normal weight concrete. Therefore, the reduction of permissible bond stress is only available for application with concretes made with weaker aggregates.

For design of ultimate bond stress for lightweight aggregate concrete, researchers tried to determine a reduction factor [98]. Tests give the result that it is not clear to measure bond strength with standard methods since the values are unrealistically high. This means it is not sensible to measure bond strength of ribbed bars in structural lightweight aggregate concrete.

Another test program is applied to investigate the effect of silica fume on the steel concrete bond in high strength lightweight concrete [97]. The bond slip behaviors are investigated in concrete mixtures. The ultimate bond stress is examined with different slip magnitude. The results show that lightweight aggregate's perfect bond slip behavior is due to its internal structure. The coherence between aggregate and the cement paste is reducing the chance of cracking. In normal weight concrete, there may be network of microcracks due to lack of harmony between aggregate and cement paste. In presence of stress, this type of concrete fails through these cracks at aggregate-paste interface.

The curing conditions and the age of specimens are examined on bond behavior of concrete and steel [99]. The bond strength is higher on pullout test compared to values in literature. Normal weight concrete with same strength value of those lightweight concretes is also subjected to pullout test. The results are higher for lightweight aggregate concrete. Also, the water curing seems to give higher bond strengths than air curing. Finally, it is seen that the bond strength increases with age.

The effect of composite action of foamed lightweight concrete is investigated [100]. For this purpose, pull-out tests performed on concrete filled with steel in different shapes namely circular and square. It is obtained that, bond strength depends on several factors such as the shape of cross section, the age and the type of concrete. Also, the bond strength of lightweight aggregate concrete is higher compared to normal weight concrete as a result of that study. On the other hand, the load-slip behavior is similar for both light weight aggregate concrete and normal weight concrete.

2.4.3.4. Fracture Behavior. There are only a few studies available for lightweight concrete [78, 101]. In all studies, the size-effect law is applied to examine fracture properties. The test performed for sintered and cold-bonded aggregate concretes. Fracture energies and

shape of size effect curves are obtained. Size effect curves showed that sintered aggregate concrete is a representative of linear elastic fracture mechanics. Also, size effect law gives a clear fit to flexural strength of lightweight aggregate concrete with different sizes [101]. Gesoglu [6] investigated the effects of lightweight aggregate type (depends on fly ash used to produce LWA), size and volume fraction (LWA content) in LWAC, w/c ratio for concrete mixture and silica fume addition to LWAC on fracture behavior of LWACs. The flexural strength value of the concretes made with 9.5 mm maximum size of LWAs was always higher than that of LWACs made with 16 mm maximum size of LWAs with both w/c ratio of 0.35 and 0.55 with or without silica fume. Silica fume addition slightly increased flexural strength (modulus of rupture) of LWAC while increasing w/c ratio affecting negatively. Flexural strength value of LWAC consisted of both lightweight and normalweight aggregates equally in volume was higher than when all the aggregates were lightweight. An increase in LWA content from 30 to 45 % of total aggregate volume resulted in approximately 10 % greater flexural strength. However, the use of LWA more than 45 % in concrete concluded with a decrease in flexural strength. As indicated by Al-khaiyat and Hague [18, 89] and Zhang and Gjorv [40] flexural strength of normalweight concrete (NWC) was approximately 1.5 times of LWC's. The use of tire rubber as aggregate with replacing ratio up to 10% in concrete ended up with significant enhancement in the flexural strength of concrete as a result of increasing energy absorbing capacity and elasticity characteristic of concrete. Decrease in flexural strength with the ratio of rubber content more than 10% generally was attributed to strength loss of rubberized concrete [25].

Khaloo *et al.* [87] also observed that concrete consisted of 25 % rubber by volume fraction of total aggregate reached its ultimate toughness value. In excess of 25% of rubber content induced a decrease in toughness of rubberized concrete owing to strength loss.

### 3. EXPERIMENTAL STUDY

In this study, an extended experimental laboratory program was conducted with the scope of studying the effects of adding polypropylene fiber and crumb rubber into the artificial lightweight fly ash aggregates which were produced by way of cold bonding process and the mechanical properties such as compressive strength, modulus of elasticity, splitting tensile strength, impact resistance, bond developed with reinforcing bar and flexural strength and toughness of structural lightweight concretes which consist of mentioned aggregates and tire chips in different mixes were investigated.

#### 3.1. Materials

During this thesis seven different materials (cement, fly ash, fibers, aggregates, steel rebar and superplasticizer) were used in order to produce both lightweight aggregate and concrete with different mixes for all production plans. All mentioned materials explained in detail as follows.

##### 3.1.1. Cement

As the first material, two types of cements used in this study. Both were TS EN 197-1 CEM I 42.5 R Portland cement obtained from Akçansa district of Istanbul, Turkey. Mechanical, chemical and physical properties of these cements which were used for the production of lightweight aggregates and concrete are illustrated in Tables 3.1, 3.2, 3.3, respectively.

Table 3.1. Mechanical properties of cements.

Mechanical Properties			
Mechanical properties/day	Standards	Test results	
		Cement (for aggregates)	Cement (for concrete)
Early Strength (2 day)	$\geq 20$ MPa	25.1	30.6
Early Strength (7 day)	-	39.5	-
Standard Strength (28 day)	$\geq 42.5$ MPa	53.7	-
	$\leq 62.5$ MPa		

Table 3.2. Chemical properties of cements.

Chemical Properties			
		Cement (used to produce fly ash aggregates)	Cement (used to produce concrete)
SiO <sub>2</sub>	(%)	20.17	20.34
Insoluble Residue	(%)	0.69	0.41
Al <sub>2</sub> O <sub>3</sub>	(%)	4.91	5.23
Fe <sub>2</sub> O <sub>3</sub>	(%)	3.41	3.37
CaO	(%)	64.28	63.25
MgO	(%)	1.18	1.23
SO <sub>3</sub>	(%)	2.84	3.00
Loss on Ignition	(%)	1.61	1.65
Cl <sup>-</sup>	(%)	0.0371	0.0458
Na <sub>2</sub> O/K <sub>2</sub> O	(%)	0.13 - 0.96	0.23 - 0.88
Unknown	(%)	0.47	0.77
S.CaO - Free Lime	(%)	1.65	1.70
Mineralogical Composition	C <sub>3</sub> S	55.65	47.41
	C <sub>2</sub> S	15.93	22.63
	C <sub>3</sub> A	7.25	8.16
	C <sub>4</sub> AF	10.38	10.26
LSF		0.97	0.94

Table 3.3. Physical properties of cements.

Physical Properties			
		Cement (used to produce fly ash aggregates)	Cement (used to produce concrete)
Specific Gravity	(g/cm <sup>3</sup> )	3.14	3.14
Initial Setting Time	(min.)	111	121
Final Setting Time	(min.)	168	183
Le Chatelier	(mm)	1	1
Specific Surface	(cm <sup>2</sup> /g)	3910	3770
Residue on 45µm sieve	(%)	14.4	4.4
Residue on 90µm sieve	(%)	2.2	0.2

### 3.1.2. Fly Ash

The fly ash used in the production of lightweight aggregate was provided by Çatalağzı Thermal Power Plant in Zonguldak. Chemical composition and specification requirements and physical properties of this fly ash are as shown in Table 3.4, Table 3.5 and Table 3.6.

Table 3.4. Chemical Composition of fly ash (%).

Chemical Composition	
SiO <sub>2</sub>	59
Al <sub>2</sub> O <sub>3</sub>	19.58
Fe <sub>2</sub> O <sub>3</sub>	7.23
CaO	0.54
MgO	4.64
SO <sub>3</sub>	0.69
Na <sub>2</sub> O	0.48
K <sub>2</sub> O	5.95
Cl <sup>-</sup>	0.0114
Free Lime	-
CaCO <sub>3</sub> +MgCO <sub>3</sub>	-
Loss on Ignition	0.49
Insoluble residue	-

Table 3.5. Chemical properties of fly ash and specification requirements.

Properties (%)	Fly ash used	ASTM C618(Class-F)
SiO <sub>2</sub> +Al <sub>2</sub> O <sub>3</sub> +Fe <sub>2</sub> O <sub>3</sub>	85.81	70 (min)
MgO	4.64	5 (max)
CaO	0.54	<10
SO <sub>3</sub>	0.69	5 (max)
Loss on Ignition	0.49	6 (max)

Fly ash complies with the requirements of Class F as limited by ASTM C 618 [102].

Table 3.6. Physical properties of fly ash.

Physical Properties		
Specific Gravity ( $\text{g}/\text{cm}^3$ )		2.06
Specific Surface ( $\text{cm}^2/\text{g}$ )		2880
Setting Time (min.)	Initial	-
	Final	-
Residue on sieves (%)	45 $\mu\text{m}$	45.2
	90 $\mu\text{m}$	25.3
	200 $\mu\text{m}$	6.5

### 3.1.3. Fibers

Dramix M12 type polypropylene fibers (PP) and crumb rubber were used in the production of lightweight aggregates and tire chips were used instead of coarse aggregates (8-16mm) part of the concrete specimens. The waste tire rubber supplied by Postaş A.Ş. Table 3.7 and Table 3.8 demonstrate the physical properties of polypropylene fibers and scrap tire rubber.

Table 3.7. Physical properties of PP.

Physical Characteristics	
Diameter ( $\mu\text{m}$ )	32
Length (mm)	12
Specific Gravity ( $\text{g}/\text{cm}^3$ )	0.91
Specific Surface ( $\text{cm}^2/\text{g}$ )	1340
Tensile Strength (MPa)	250
Modulus of Elasticity (GPa)	3.5-3.9
Fiber Number (Fibers/kg)	110 Million
Melting Point ( $^{\circ}\text{C}$ )	165

Table 3.8. Physical properties of tire rubber.

Physical Properties	Tire Rubber	
	Crumb Rubber	Tire Chips (TC)
Specific Gravity (g/cm <sup>3</sup> )	0.83	1.02
Particle Size (mm)	4 (max)	10-40
Fineness Modulus	1.39	-

### 3.1.4. Aggregates

As fine aggregates, natural sand and crushed sand and as coarse aggregates, crushed stone No-1 (4-8 mm) and No-2 (8-16 mm) were incorporated in the concrete production as well as artificial lightweight fly ash pellets that were produced having different physical properties through cold bonding process. The maximum grain size of the aggregates was 16 mm. The physical characteristics of the aggregates used are presented in Table 3.9.

Table 3.9. Properties of aggregates.

Aggregates		Unit Weight (g/cm <sup>3</sup> )
Fine Aggregates	Natural Sand	2.65
	Crushed Sand	2.70
Coarse Aggregates	Crushed Stone No-1	2.70
	Crushed Stone No-2	2.70

Physical properties of lightweight aggregates will be given below under its own caption.

3.1.4.1. Preparation of Lightweight Coarse Aggregates. Lightweight fly ash pellets were produced through the cold-bonding agglomeration process by a pelletization disc. The pelletizer disc runs with the original functioning principles of the devices used in the industrial plants. The details of the pelletizer disc sketched in Figure 3.1. The rotation

speed of the disc is managed via a speed controller unit by changing the frequency range between 0 to 45 rpm with 0.01 sensitivity. The angle of the disc plane to the normal is regulated by means of a divisor table with  $1/30^\circ$  sensitivity. The pelletizer pan has diameter of 40 cm and height of 15 cm. Besides, the disc has scrapping blades which arranged to provide different grain size of spherical shaped material which moved in various paths (coarse size material in interior path while fine size in outer path) in order to have a clear observation of the grain size distribution. Moreover, with the scope of ensuring more compacted fresh pellets, an energy barrier was installed [4]. A schematic view of the disc plane is exhibited in Figure 3.2.

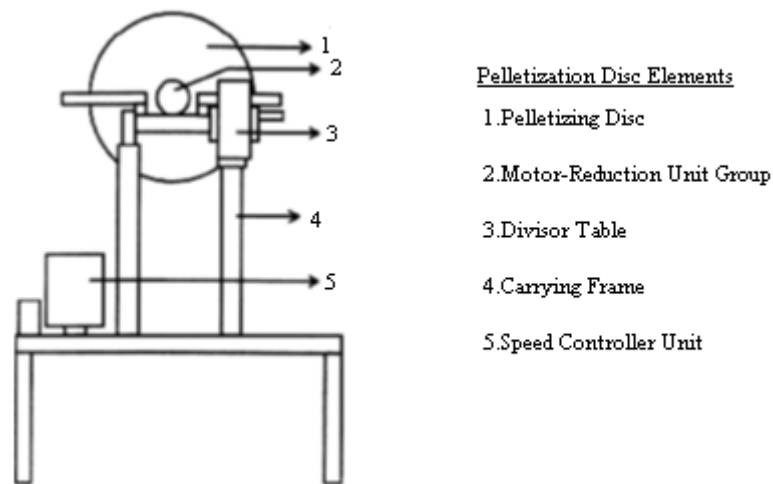


Figure 3.1. Pelletization Disc.

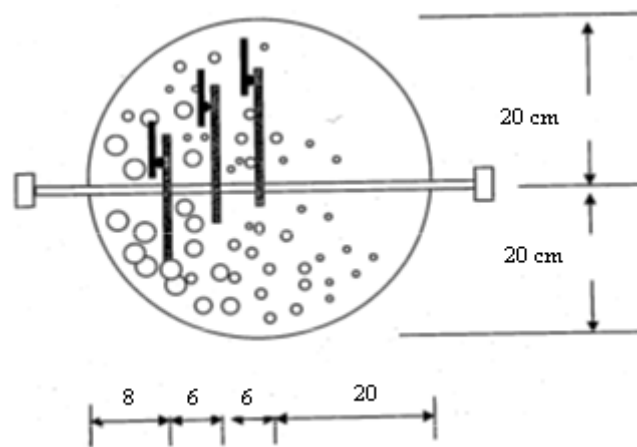


Figure 3.2. General view of the disc.

With respect to the results of Döven [4], inclination angle of the disc and optimum rotation speed were fixed at  $43^\circ$  and 45 rpm, respectively. With the purpose of having homogeneous mixture, the disc was rotated at a constant speed and angle after having fed the dry fly ash-cement mixture to produce plain lightweight pellets and the dry fly ash-cement-fibers to produce fiber reinforced lightweight pellets into the pan. In the next step, the powder mixtures placed into the pelletization disc and water was sprayed onto the powder mixtures during the first 10 minutes of the agglomeration process with an amount of 23-27 % of the total weight of material to get the spherical pellets. At that period, avoiding water film on the surface of the pellets was extremely important in order to have pellets separated finally as single aggregates so the amount of water sprayed to produce pellets was determined with the preliminary production tests. Although the pellet formation originated in the first 10 minutes, extra 10 minutes allocated to the further compaction of the fresh pellets to increase the strength properties, hence making the total pelletization operation 20 minutes. In this way, artificial lightweight aggregates were produced from the fly ash with a cement-to-fly ash ratio of 0.1 by weight.

Polypropylene fiber (PP) and crumb rubber were added to the dry mixture of plain/control lightweight aggregates with different ratios to produce fiber reinforced lightweight aggregates as different composites in different fiber amounts. This makes it possible to compare the lightweight aggregate properties and the mechanical properties of the concrete specimens within themselves. Materials used to produce lightweight pellets are presented as in Figure 3.3.



Figure 3.3. Materials used to produce lightweight pellets.

As the first step of experiments, plain/control lightweight aggregates (LC) produced with the purpose of comparison with lightweight aggregates reinforced by 0.1 % of crumb rubber (L1P), 0.2 % of crumb rubber (L2P), 0.3 % of crumb rubber (L3P), 0.5 % of crumb rubber (L5P) as well as 0.1 % of polypropylene (L1F) and 0.2 % of polypropylene (L2F) fibers.

Since the results of preliminary crushing strength test of crumb rubber reinforced lightweight aggregates demonstrated significant differences just between L1P and L5P particles, it has been decided to eliminate L2P and L3P for the future essential tests and concrete production. In addition, when reinforcing the lightweight aggregates by 0.2 % of polypropylene fiber through cold bonding agglomeration process, production faced with a problem of not embedding the PP fibers to pellets completely therefore production of L2F also was cancelled.

When the fresh pellets had been made, they were preserved in confined plastic bags as in Figure 3.4 and left for the final hardening inside a curing room at a temperature of 20 °C and 80 % relative humidity for 28 days.



Figure 3.4. Lightweight aggregates in sealed plastic bags.

3.1.4.2. Tests and Measurements on Lightweight Aggregate Grains. After curing period the hardened lightweight aggregates were separated into two fractions in diameters of 4-8 mm and 8-16 mm to be used instead of coarse aggregates No-1 and No-2 respectively as shown in Figure 3.5. The grains larger than 16 mm and smaller than 4 mm were discarded. Then, predetermined physical and mechanical tests were performed on the aggregates in the range of 4 mm and 16 mm.

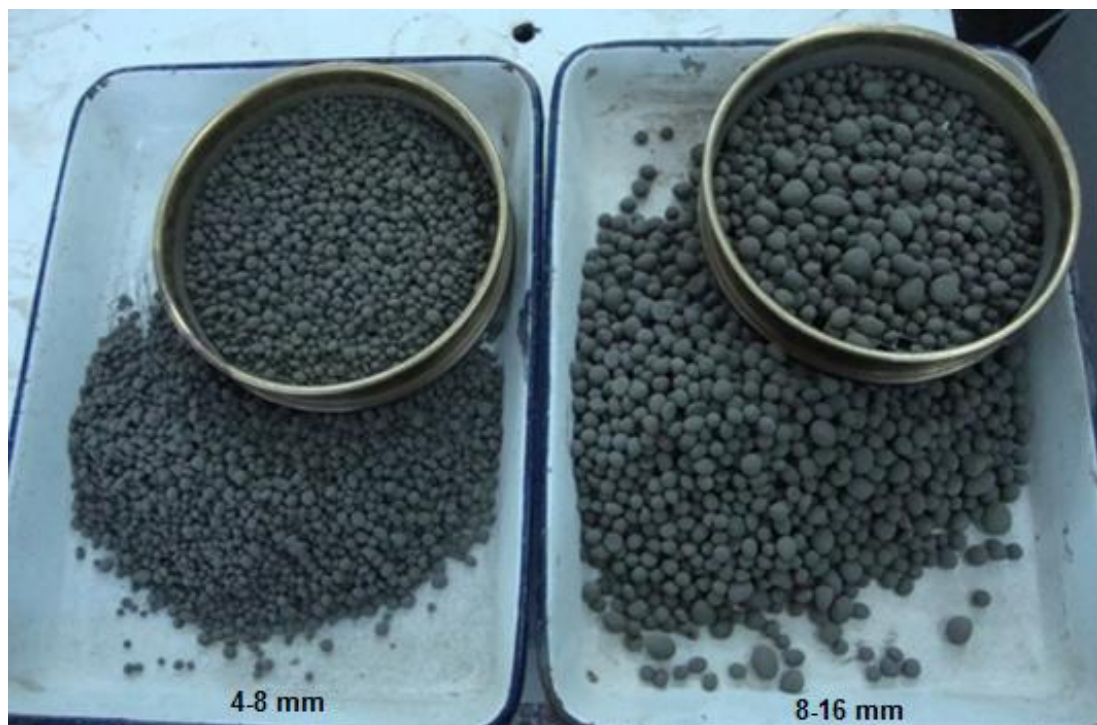


Figure 3.5. The separated lightweight aggregates into two groups.

*Unit Weight, Specific Gravity, and Water Absorption:* Physical properties of lightweight aggregates such as unit weight (ASTM C 29), specific gravity and water absorption (ASTM C 127) were determined according to specified standards [103, 104].

*Crushing Strength:* In this study, strength of the lightweight aggregates was specified by calculating the crushing strength of individual pellets that were placed one by one between two parallel plates to be loaded diametrically with increasing force measured by a 4.5 kN capacity load ring with 0.5 mm/min loading speed until the failure occurs as shown in Figure 3.6.

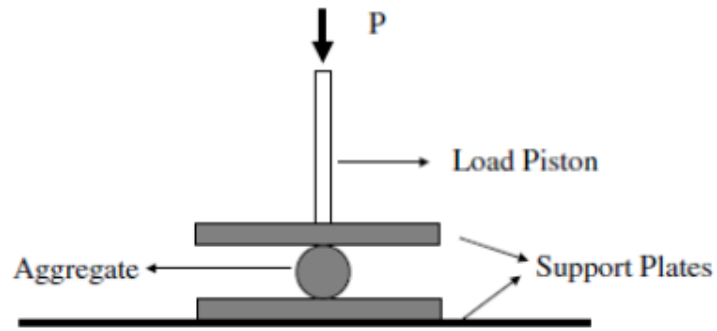


Figure 3.6. Aggregate crushing strength configuration.

Stress analysis shows that the crushing strength  $\sigma$  is given by:

$$\sigma = \frac{2.8 \cdot P}{\pi \cdot X^2} \quad (3.1)$$

where P is the failure load and X is the distance between loading points [47, 61-64]. Forty pellets had an average diameter of 12 mm were tested in order to calculate the average crushing strength for each types of aggregates.

*Microscopic Observation:* As the next step of this study, optical microscopic observation performed to have a better visual distribution observation of fibers in pellets and to check whether the pellets were ingenerated as a single core or spherical layers shaped pellet.

### 3.1.5. Reinforcing Steel

Deformed steel bars (S420) which had a diameter of 12 mm, were used to determine the bond strength through pull-out test.

### 3.1.6. Superplasticizer

A new generation of superplasticizer, called Rheobuild 1000 which is an ASTM C494 [105] Type F high range water-reducing superplasticizer that contains sulphonated polymer, was used in the concrete mixes in order to get the slump of  $14 \pm 2$  cm.

Table 3.10. Properties of superplasticizer.

Color	Dark Brown
Physical State	Liquid
Odor	Musty
Specific Gravity	1.21
pH	Approx. 7.0
Chloride Content	$\leq 0.1\%$ (TS EN 480-10)
Alkali Content	$\leq 5\%$ (TS EN 480-12)
Boiling Point	212 °F (100 °C)
Freeze Point	28 °F (-2 °C)
Water Solubility	Completely Soluble

### 3.2. Concrete Mix Design and Casting Procedure

#### 3.2.1. Aggregate Grading

The experiments of sieve analysis performed to both natural and crushed sand as fine aggregates and crushed stone as coarse aggregate. The outcomes of the analysis are given in Table 3.11.

Table 3.11. Sieve analysis of the aggregates.

Sieve Size (mm)	Percent Passing (%)			
	Crushed Stone		Crushed Sand	Natural Sand
	No-1	No-2		
16.00	100	100	100	100
8.00	100	0	100	100
4.00	0	0	98.22	100
2.00	0	0	63.06	100
1.00	0	0	37.59	99.90
0.50	0	0	21.52	99.81
0.25	0	0	11.96	12.38

With respect to the results of the sieve analysis, it has been decided to mix crushed stone, natural sand and crushed sand in proportions of 55, 13 and 32 % of the total aggregate volume, respectively. Since there were two types of crushed stone called No-1 and No-2, experiments conducted on both of them and according to the results the final crushed stone mixture consisted of 50% of No-1 and 50% of No-2. At last, a grading curve of each volume concentration and particle size drawn in Figure 3.7 in order to use in the ultimate concrete mixture concerning the limitations advised by TS 706 EN 12620.

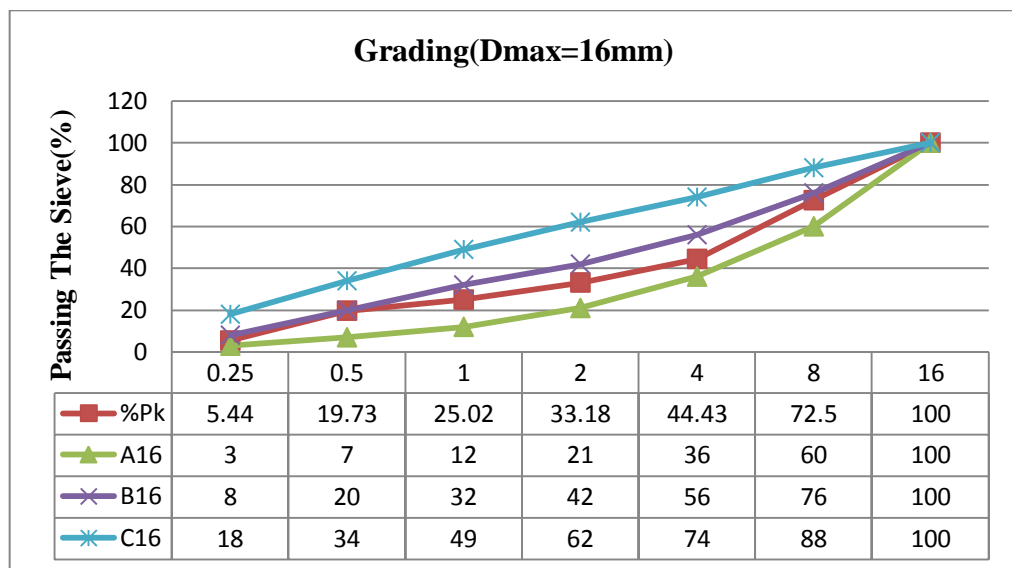


Figure 3.7. Aggregate grading.

### 3.2.2. Concrete Mix Design

Concrete mixes were cast by using Portland cement, fine and coarse aggregates, water and superplasticizer. Water and cement were used in constant quantity; water 180 kg/m<sup>3</sup> and cement 450 kg/m<sup>3</sup> so that water to cement ratio was 0.40 in all series of concrete production plan. Superplasticizer used in all mixes in different ratios in order to provide the required slump. As water and binder, fine aggregates; natural sand and crushed sand were also used in fixed amounts; 228 kg/m<sup>3</sup> and 570 kg/m<sup>3</sup> in all concrete series, respectively. As coarse aggregates (diameter of 4-16mm), crushed stone No-1 (having the diameter of 4-8 mm) and No-2 (having the diameter of 8-16 mm), LC, L1P, L5P, L1F and tire chips were used as mentioned above. LC, L1P, L5P, L1F replaced with crushed stone No-1 and No-2 in the case of different productions, however tire chips used just as No-2.

For instance, a series namely LC(4-8mm)CSt(8-16mm) represents that lightweight plain/control aggregates and crushed stone were used for the coarse aggregate No-1 and No-2, respectively where the lightweight aggregates reinforced by 0.1 % of crumb rubber used as No-1 and tire chips (TC) as No-2 in the production of LIP(4-8mm)TC(8-16mm). Mix proportions of 18 different series as all production plans are given in Table 3.12.

### **3.2.3. Concrete Casting**

50 dm<sup>3</sup> capacity of concrete mixer was used for concrete production. For each series of production plan, 48 dm<sup>3</sup> concrete that was needed according to predetermined experiments produced as two mixtures in different volumes; one is 22 dm<sup>3</sup> and the other is 26 dm<sup>3</sup>, to utilize the mixer efficiently for homogeneity of concrete. A special procedure was applied for concrete casting to minimize the slump loss owing to the high water absorption of the lightweight aggregates. For this aim, lightweight aggregates were submerged in water for 24 hours to be water saturated then kept on large scale sieves for extra 1 hour to have as surface dry sample before mixing. The mixing procedure of concrete consisted of dry mix of aggregates with cement for two minutes. Then water with superplasticizer was added gradually into the dry mix in one minute. After all the materials were mixed for another two minutes, the concrete was ready to measure fresh mix properties such as slump and unit weight before casting the concrete into the moulds in two layers both of which being vibrated.

### **3.2.4. Specimens and Curing Conditions**

After casting, all the specimens were finished by using a steel trowel and the specimens were covered with nylon sheets to minimize water loss. Then, the specimens were left in laboratory environment for 24 hours before demoulding. Following that, cylinder and beam specimens were labeled and moved to the curing room at a temperature of 20 °C and 85 % relative humidity for 56 and 90 days before testing, respectively.

Cylinder and beam specimens were produced for each series of the research. Type of tests and dimensions and numbers of the specimens cast throughout the production process are as presented in Table 3.13.

Table 3.12. The mix proportions used in the experiments (kg/m<sup>3</sup>) (SP\* stands for superplasticizer).

Production Plan				Fine Aggregates		Coarse Aggregates						SP		
	W/C (%)	Cement	Water	Natural Sand	Crushed Sand	Crushed Stone		LC	L1P	L5P	L1F	TC	(%)	(kg/m <sup>3</sup> )
						No 1	No 2							
CCSt(4-16)	40	450	180	228	570	490	490	-	-	-	-	-	1.2	5.4
CSt(4-8)TC(8-16)	40	450	180	228	570	490	-	-	-	-	-	185.1	3	13.5
<b>LC(4-8)CSt(8-16)</b>	40	450	180	228	570	-	490	290.37	-	-	-	-	1	4.5
<b>LC(8-16)CSt(4-8)</b>	40	450	180	228	570	490	-	290.37	-	-	-	-	1	4.5
<b>LC(4-8 and 8-16)</b>	40	450	180	228	570	-	-	580.74	-	-	-	-	1	4.5
L1P(4-8)CSt(8-16)	40	450	180	228	570		490	-	292.19	-	-	-	1	4.5
L1P(8-16)CSt(4-8)	40	450	180	228	570	490	-	-	292.19	-	-	-	1	4.5
L1P(4-8 and 8-16)	40	450	180	228	570	-	-	-	584.38	-	-	-	1	4.5
<b>L5P(4-8)CSt(8-16)</b>	40	450	180	228	570	-	490	-	-	292.19	-	-	1	4.5
<b>L5P(8-16)CSt(4-8)</b>	40	450	180	228	570	490	-	-	-	292.19	-	-	1	4.5
<b>L5P(4-8 and 8-16)</b>	40	450	180	228	570	-	-	-	-	584.38			1	4.5
L1F(4-8)CSt(8-16)	40	450	180	228	570	-	490	-	-	-	290.37	-	1	4.5
L1F(8-16)CSt(4-8)	40	450	180	228	570	490	-	-	-	-	287.26	-	1	4.5
L1F(4-8 and 8-16)	40	450	180	228	570	-	-	-	-	-	577.63	-	1	4.5
<b>LC(4-8)TC(8-16)</b>	40	450	180	228	570	-	-	290.37	-	-	-	185.1	3	13.5
<b>L1P(4-8)TC(8-16)</b>	40	450	180	228	570	-	-	-	292.19	-	-	185.1	3	13.5
<b>L5P(4-8)TC(8-16)</b>	40	450	180	228	570	-	-	-	-	292.19	-	185.1	3	13.5
<b>L1F(4-8)TC(8-16)</b>	40	450	180	228	570	-	-	-	-	-	290.37	185.1	3	13.5

Table 3.13. The type of test and dimensions and numbers of the specimens.

Production Plan	Cylinder Specimens(100*200 mm)			Cylinder Specimen (150*300 mm)	Beam Specimens (100*100*500 mm)	Total
	Compressive strength and Modulus of Elasticity	Splitting Tensile Strength	Pull-Out Test (12mm diameter of ribbed bars embedded)	Failure Impact Energy	Flexural Strength and Toughness	
CCSt(4-16)	3	3	3	3	3	15
CSt(4-8)TC(8-16)	3	3	3	3	3	15
<b>LC(4-8)CSt(8-16)</b>	3	3	3	3	3	15
<b>LC(8-16)CSt(4-8)</b>	3	3	3	3	3	15
<b>LC(4-8 and 8-16)</b>	3	3	3	3	3	15
L1P(4-8)CSt(8-16)	3	3	3	3	3	15
L1P(8-16)CSt(4-8)	3	3	3	3	3	15
L1P(4-8 and 8-16)	3	3	3	3	3	15
<b>L5P(4-8)CSt(8-16)</b>	3	3	3	3	3	15
<b>L5P(8-16)CSt(4-8)</b>	3	3	3	3	3	15
<b>L5P(4-8 and 8-16)</b>	3	3	3	3	3	15
L1F(4-8)CSt(8-16)	3	3	3	3	3	15
L1F(8-16)CSt(4-8)	3	3	3	3	3	15
L1F(4-8 and 8-16)	3	3	3	3	3	15
<b>LC(4-8)TC(8-16)</b>	3	3	3	3	3	15
<b>L1P(4-8)TC(8-16)</b>	3	3	3	3	3	15
<b>L5P(4-8)TC(8-16)</b>	3	3	3	3	3	15
<b>L1F(4-8)TC(8-16)</b>	3	3	3	3	3	15
<b>Total</b>	54	54	54	54	54	270

### 3.3. Tests and Measurements for Fresh Concrete

#### 3.3.1. Slump Test

The slump test was performed on fresh concrete immediately after production according to ASTM C 143 [106]. A slump cone was filled with concrete in three layers and each layer was approximately one third the volume of the cone and was hit with 25 strokes by using a tamping rod. As soon as the cone filled with concrete, it was removed from the concrete by raising it in vertical direction. The slump was immediately measured by

determining the vertical distance between the top of the cone and the displaced original center of the top surface of the concrete.

### 3.3.2. Air Content and Density Test on Fresh Concrete

The fresh density and air content test was conducted in general compliance with the standard procedure in ASTM C 138 [107]. Concrete was placed in a cylindrical container with vibratory table unit. After consolidation, mass of the container filled with concrete was measured. By using volume and mass of container, density of fresh concrete was calculated according to Equation 3.2.

$$D = (M_c - M_m) / V_m \quad (3.2)$$

The air content was calculated as follows:

$$A = \frac{\frac{M}{V} - D}{\frac{M}{V}} * 100 \quad (3.3)$$

Where, D is the density (unit weight) of concrete, kg/m<sup>3</sup>, A is the air content (percentage of voids) in the concrete, M<sub>c</sub> refers to mass of the measure filled with concrete, kg, M<sub>m</sub> refers to mass of the measure, kg, V<sub>m</sub> is the volume of the measure, m<sup>3</sup>, M is the total mass of all materials batched, kg, V refers to total absolute volume of the component ingredients in the batch, m<sup>3</sup>.

### 3.4. Tests for Determination of Mechanical Properties of Hardened Concrete

At the end of residence time in the curing room, on the specimens of 22 dm<sup>3</sup> casting, impact and pull-out tests and on the specimens of 26 dm<sup>3</sup> casting, compressive, modulus of elasticity, splitting tensile and fracture tests were performed.

### 3.4.1. Compressive Strength and Modulus of Elasticity

Compressive strength test were performed on the cylinder specimens (100x200 mm) at the age of 56 days with a capacity of 2000 kN testing machine. The test was carried out as described in ASTM C39 “Standard Test Method for Compressive Strength of Cylindrical Concrete Specimen”. To have parallel loading faces for uniform stress distribution and constant height for all cylinders, specimens were capped prior to testing with a sulphur concentrated mortar in conformity with the specification of ASTM C 617 [108]. Cylinders were loaded axially at a constant rate of 2.4 kN/sec until failure occurred.



Figure 3.8. Compressive strength and modulus of elasticity test.

Modulus of elasticity of the same cylinders on which compressive strength test applied measured in accordance with ASTM C 469 “Standard Test Method for Static Modulus of Elasticity and Poisson’s Ratio of Concrete in Compression” at the age of 56 days. Longitudinal strain is defined as the total longitudinal deformation divided by the effective gage length. Longitudinal deformations of the specimens under loading were measured by the help of two LVDTs (linear variable differential transformers) connected to a data recorder system as shown in Figure 3.8. By using these data set longitudinal strain

which is defined as the total/final longitudinal deformation divided by the effective gage length, was calculated by the aid of these LVDTs. For determination of modulus of elasticity, load-displacement curves are used. The slope of such curve gives the value of modulus of elasticity.

### 3.4.2. Splitting Tensile Strength

Splitting tensile strength tests of concretes were conducted on 100×200 mm cylinders at the age of 56 days in accordance with ASTM C 496 “Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens”. The test was done by implementation of compressive loads which applied in diametrically opposite direction to a concrete cylinder laid on its side in the testing machine exhibited in Figure 3.9. Fracture or “splitting” revealed along the diametric plane. The load was applied at a constant rate of 0.94 kN/s. The maximum applied load and splitting tensile strength were indicated by the testing machine at failure.



Figure 3.9. Splitting tensile strength test.

### 3.4.3. Impact Resistance

For determination of impact resistance known as the dynamic energy absorption as well as strength of the concrete specimens, “repeated impact” or “drop-weight” test was preferred to alternatives mentioned in ACI 544.2R “Measurement of Properties of Fiber Reinforced Concrete” for the sake of simplicity. Drop-weight impact test was applied to cylinder disks of 63.5 mm thickness, sliced from 150\*300 mm cylinder specimens (at the age of 56 days). This test is conducted with equipment that consists of a standard, manually operated compaction hammer (4.54 kg) with a drop length of 457 mm (ASTM D 1557 [109]), a hardened steel ball has a diameter of 63.5 mm and a flat base plate similar to that shown in Figure 3.10 and 3.11 as described in ACI 544.2R code.

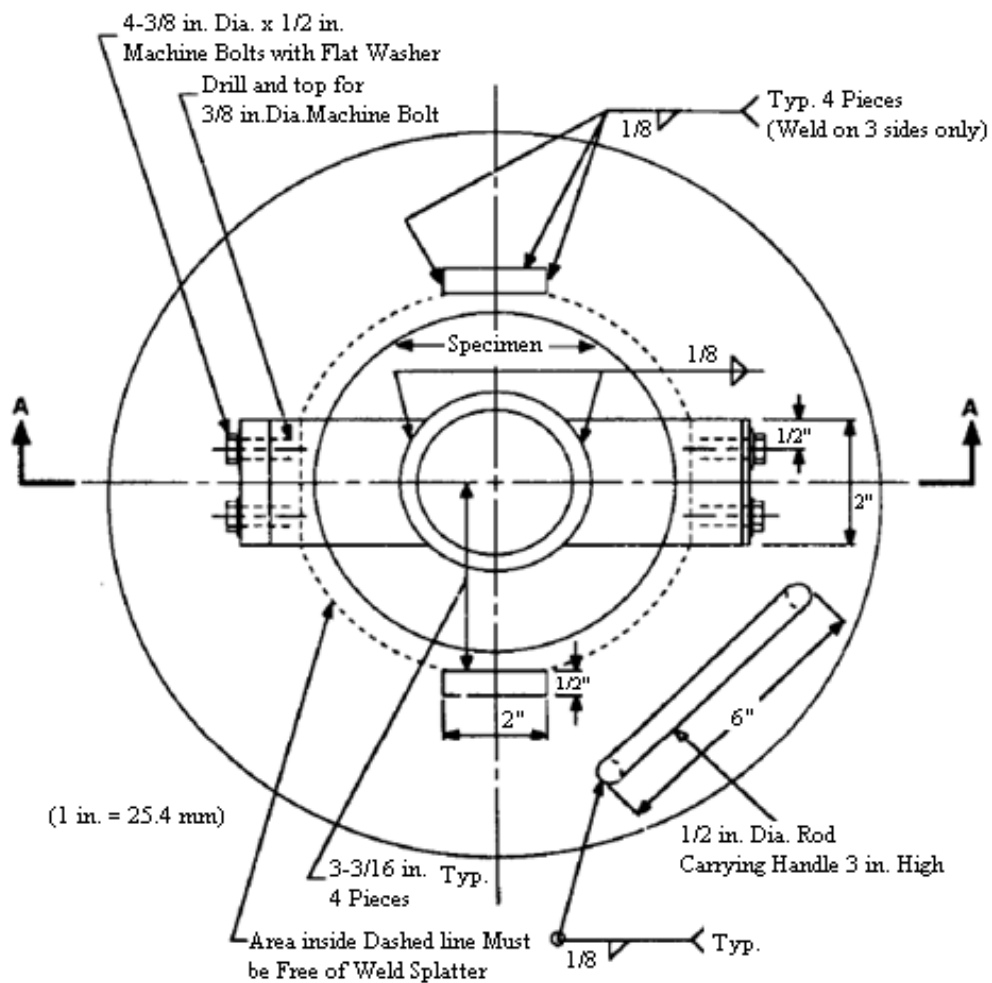


Figure 3.10. Plan view of test equipment for impact resistance.

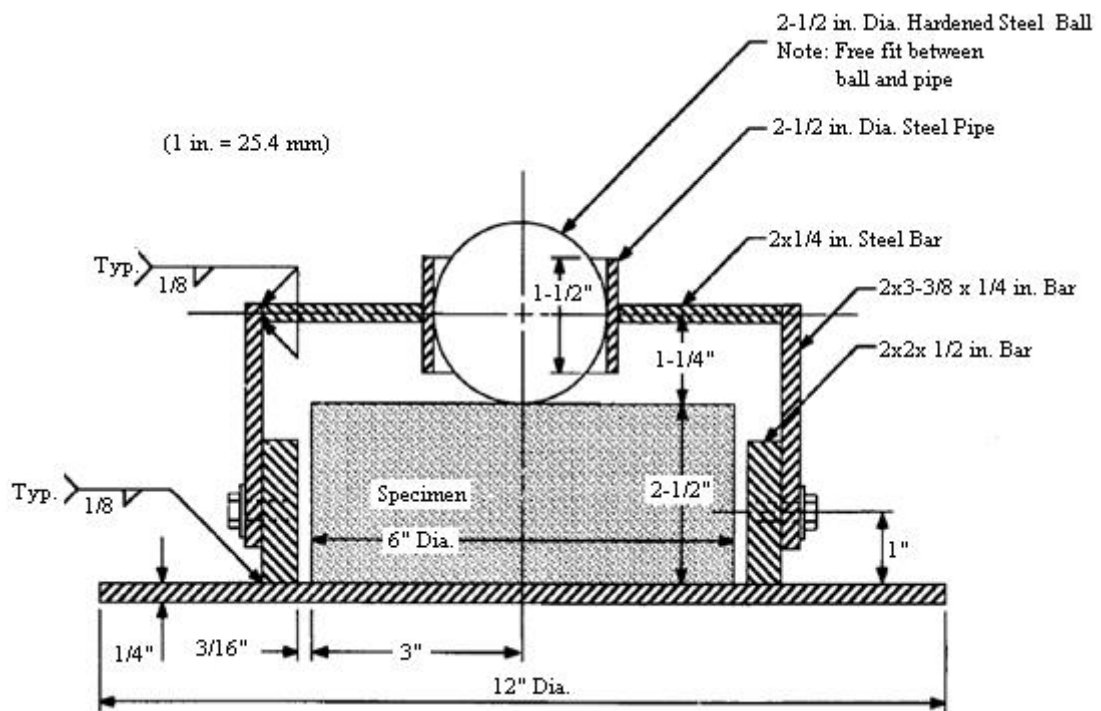


Figure 3.11. The view of section A-A on test equipment presented in Figure 3.10.

As the initiation of the experiment, the bottom of the cylindrical disk samples were coated with a thin layer of heavy grease and placed on the base plate within the positioning lugs with the finished face up and the whole mentioned equipment was fixed to the floor. Then, the hardened steel ball put to the top of the disk specimen within the bracket. With the purpose of preventing the movement of the specimen during testing till the first visible crack, steel pieces were placed between the disk specimen and positioning lugs. Afterwards, the drop hammer was placed with its base above the steel ball and held there by applying enough pressure up to the end of the test. The hammer was dropped repeatedly and the number of blows required to induce the first visible crack on the top of specimen and to result in ultimate failure were both recorded. When the initial visible crack was observed the steel pieces were removed. It is assumed that ultimate failure reached when the pieces of concrete touched to three of four positioning lugs on the base plate.

General formula for calculation of impact energy per blow of the hammer as reported by Mohammadi *et al.* [94] and Gopalaratnam and Shah [96] is given by the following expressions:

$$H = \frac{gt^2}{2} \quad (3.4)$$

$$V = gt \quad (3.5)$$

$$m = \frac{W}{g} \quad (3.6)$$

$$U = \frac{mV^2}{2} \quad (3.7)$$

where  $g$  is acceleration due to gravity;  $t$  is time taken by the hammer to fall a height of 457 mm,  $H$  is height of fall,  $V$  is velocity of the hammer at impact moment,  $m$  is mass of the hammer,  $W$  is the weight of hammer and  $U$  is impact energy per blow of the hammer.

Substituting the relevant values in Equation 3.4;

$$457 = \frac{9180 * t^2}{2} \rightarrow t = 0.3155 \text{ sec}$$

$$V = 9810 * 0.3155 = 2896.29 \text{ mm/sec}$$

$$U = \frac{4.54 * (2896.29)^2}{2} = 19038.72 \text{ N.mm}$$

#### 3.4.4. Pull-Out Test (Bond Developed with Reinforcing Bar)

In order to measure reinforcing bar-concrete bond capacity in lightweight concrete, pullout test was applied to 100×200 mm cylinders (at the age of 56 days) with a single ribbed bar embedded vertically along the central axis in compliance with ASTM C 234 [110]. At the bottom of the mould, there was a space of 10 mm height to place rebar out of concrete at the end of casting process. The rebar was placed in the middle of this space, created by using a special apparatus with a hole at the center. After that, mould was filled by concrete. The anchorage length of deformed steel bar (S420) which had a diameter of 12 mm, was 100 mm. For the application of efficient loading, the bar length had to be 120 cm. The test was performed using a capacity of 1000 kN universal testing machine. The test setup is shown in Figure 3.12.

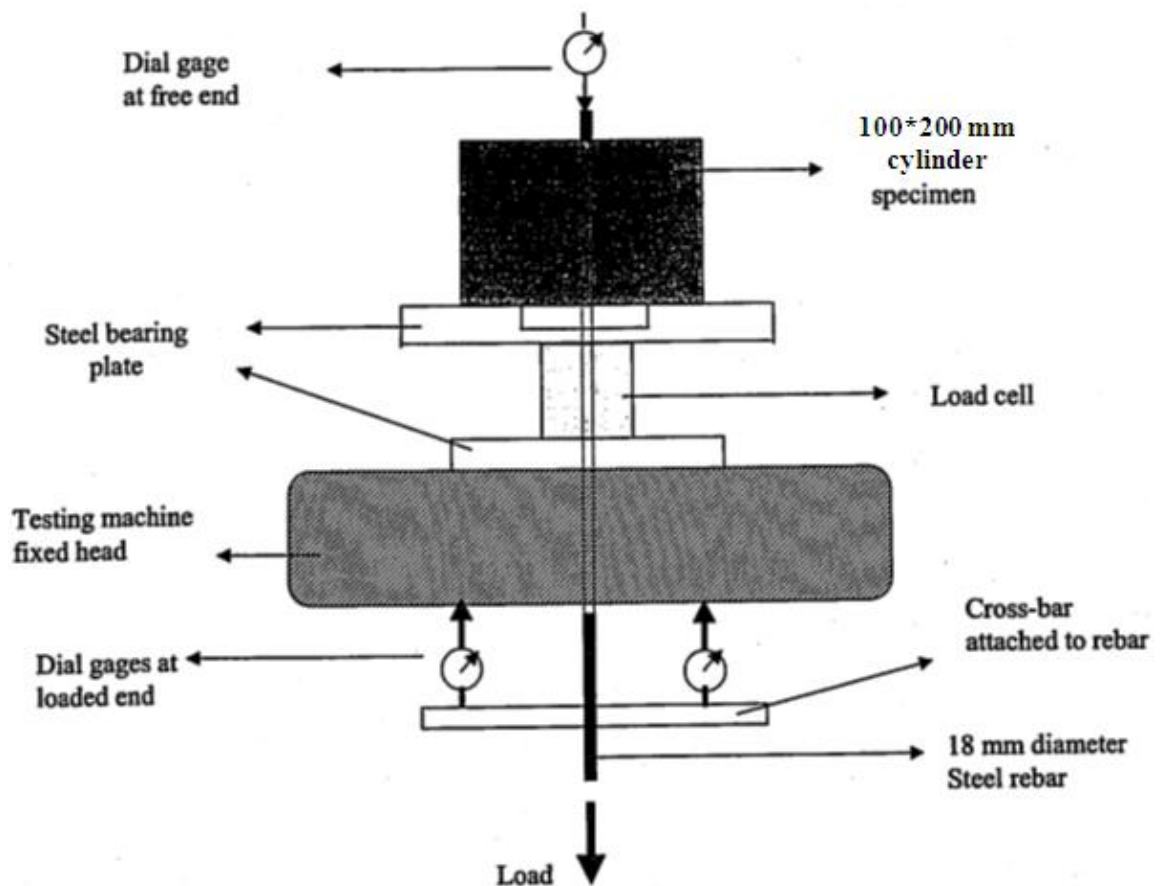


Figure 3.12. Test setup for pull-out test

Reinforcing bar was gripped in jaws which installed on the moving head of testing device and the bar was pulled by means of the fixed head supporting the concrete specimen. A load cell with a capacity of 100 kN was used to measure the pull force that applied to the steel bar of the specimen. Data logger system collected the load and displacement results of the experiment by the help of mentioned load cell and dial gages, respectively.

With the scope of measuring the slip, two dial gages were attached to the steel bar at the loaded end below the stationary head. Besides, another dial gage was also mounted at the free end of the reinforcing bar in order to measure the free-end slip.

All tests were conducted at appropriate loading speed until the maximum load value had been reached without any yielding of steel bars. During this process, concrete specimens of all series with tire chips as coarse aggregate split when the load applied

reached to the ultimate value; however the remaining group of series which contain tire chips showed longitudinal cracks characteristics without splitting.

According to the average maximum load of each series ultimate bond strength values at a slip of 0.25, 0.50, 1.00 mm were calculated with the formula as defined below [110]:

$$\tau_u = \frac{P_{max}}{\pi DL} \text{ (MPa)} \quad (3.8)$$

where  $P_{max}$  is the ultimate pullout load and L and D are the bond length and diameter of the reinforcement bars, respectively.

### 3.4.5. Flexural Strength and Toughness

Flexural strength tests were conducted in order to obtain ultimate strength and deflection at the midsection before failure, so that flexural strength and toughness. For this purpose a MTS Landmark Closed-Loop Displacement Controlled Dynamic Testing Machine with a 100 kN capacity was used. Three 100x100x500 mm un-notched beam specimens for each series were statically loaded under three point loading. Loading was applied at a rate of 0.02 mm/sec. Displacement of stroke was used for vertical displacement of specimens. The beam specimens were turned on their side so as to use a plain and smooth surface. A scheme of the test setup is seen in Figure 3.13.

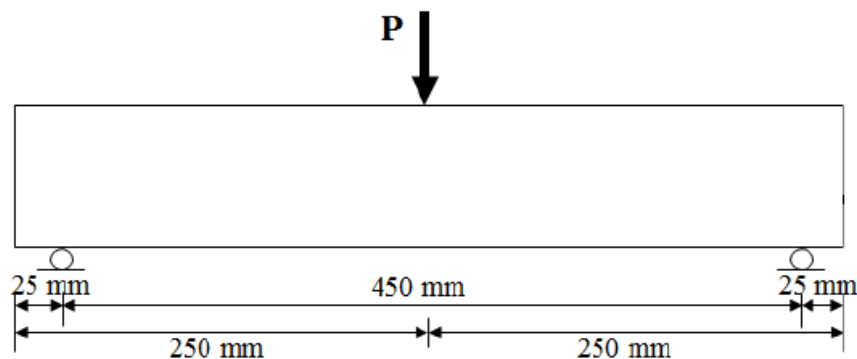


Figure 3.13. Three point flexure test setup.

Flexural strength was calculated with the formula recommended by ASTM D 7264 [111] as follows:

$$\sigma = \frac{3PL}{2bh^2} \quad (3.9)$$

where,  $\sigma$  is the stress at mid-span, MPa, P is the applied force, N, L is the support span, mm, b refers to width of beam, mm, h refers to thickness of beam, mm.

The toughness of plain and fiber-reinforced concrete can be regarded as their energy absorption capacity, which is the area under the load-deflection curve obtained during a flexure/bending test as reported by JSCE SF-4 (Standard SF-4 method of Japan Society of Civil Engineers).

## 4. TEST RESULTS AND EVALUATION

In this chapter, LWA properties are examined and the test results of both fresh and hardened concrete are also underlined.

### 4.1. Lightweight Aggregate Properties

Crushing strength and physical properties such as unit weight, specific gravity and water absorption of LWAs that were produced with fly ash and cement as a binder by cold bonding process are given below.

#### 4.1.1. Unit Weight, Specific Gravity and Water Absorption

After 28 days curing time in humid room at a temperature of 20°C and 80% relative humidity, tests and measurements were applied to LWAs according to ASTM C29(unit weight) and ASTM C127( specific gravity and water absorption).

Average unit weight and specific gravity values of LWAs are approximately 1.00 and 1.60 respectively that are lower than unit weight and specific gravity of normalweight aggregate due to porous structure of LWA, density of materials used to produce fly ash pellets, amounts of water used to obtain pellet formation and absence of any treatment of cold-bonded pellets such as water glass and slurry. Besides, while oven-dry specific gravity values of LWAs in the size of 4-8 mm are lower than that of LWAs in the size 8-16 mm, water absorption values of the former are higher than the latter. At that point it has to be considered that when grain size of a single pellet grows, fiber content existing inside the body of a pellet increases. This may also result in having both closed and open pores and so permeability.

Saturated-surface-dry specific gravity, bulk density and water absorption of cold-bonded lightweight fly ash aggregates with various ratios of cement to fly ash(Class F) were investigated by Chi *et al.* [77]. When content of cement with higher specific gravity than that of fly ash increased, both specific gravity and bulk density of fly ash pellet showed an increment with a reduction of water absorption due to the decrease in porosity.

The specific gravity of LWA with the same ratio of cement to fly ash that was used in this study (10% by weight) is slightly higher than what is obtained for any type of aggregates shown in Table 4.1.

Table 4.1. Physical properties of LWAs.

	LC		L1P		L5P		L1F	
	4-8 mm	8-16mm	4-8 mm	8-16mm	4-8 mm	8-16mm	4-8 mm	8-16mm
<b>Unit Weight, <math>\beta</math>(g/cm<sup>3</sup>)</b>	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
<b>W<sub>dry</sub>(105°C, 24h),g/lit</b>	405.5	404.3	403.2	404.1	404.4	404.2	404.0	410.0
<b>W, g/lit</b>	520.0	503.0	515.5	501.5	516.0	505.0	506.5	510.5
<b>W<sub>iw</sub>, g/lit</b>	195.5	188.0	194.5	190.0	195.0	190.5	190.0	188.0
<b>Specific Gravity<sub>ssd</sub></b>	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6
<b>Specific Gravity<sub>od</sub></b>	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3
<b>Water Absorption, %</b>	28.2	24.4	27.9	24.1	27.6	24.9	25.4	24.5

In this project, cold-bonded lightweight fly ash aggregates with cement as a binder were produced with the same proportions of another study [60]. Fly ash is also the same with fineness of 2880 cm<sup>2</sup>/g and specific gravity of 2.06. Although cement is different in fineness (higher) and specific gravity (slightly lower), results for specific gravity and water absorption of LWAs are approximately the same.

#### 4.1.2. Crushing Strength

In this study, strength of the lightweight aggregates was specified by calculating the crushing strength of individual pellets that were placed one by one between two parallel plates to be point loaded with increasing force measured by a 4.5 kN capacity load ring with 0.5 mm/min loading speed until the failure occurs. Forty pellets with an average diameter of 12 mm were tested in order to calculate the average crushing strength for each type of aggregate. Crushing strength values were calculated according to Equation 3.1 that was given in Chapter 3.

Table 4.2. Crushing strength values of LWAs.

	$\sigma(\text{N/mm}^2)$	$\sigma(\text{standart deviation})$
<b>LC</b>	3.78	0.89
<b>L1P</b>	4.19	0.84
<b>L5P</b>	3.90	0.92
<b>L1F</b>	3.53	0.86

It is expected that addition of crumb rubber into the pellets with the ratio of 0.1% (L1P) and 0.5% (L5P) increases the impact strength values. However, as seen in Table 4.2, crumb rubber addition also increased the crushing strength values. This implies that in aggregate dimensions, crumb rubber addition not only increases the impact strength but also the crushing strength. This contradicts with the general view on compressive strength behavior of concrete specimens; which is replacing the coarse aggregate by tire chips in concrete decreases compressive strength but greatly increases the impact strength. This may be accounted firstly for the adherence problem between tire chips and the matrix of lightweight concrete with cold bonded pellets, and secondly for the extra void entrapped by tire chips and thirdly for the difference in the failure mechanism in the fly ash pellets under point load and in concrete under compressive load.

As it is known in the literature, polypropylene fiber addition to the concrete increases tensile strength drastically while contributing minimally to compressive strength. In this study average crushing strength values for L1F was slightly lower than that of LC. However, if we consider the standard deviation for the crushing strength values of LC and L1F, results are approximately the same.

#### 4.1.3. Microscopic Observation

Optical microscopic observation was performed to have a clear view of fiber distribution in pellets, and to check whether the pellets were generated as a single core or shaped in spherical layers.

As seen in Figure 4.1, crumb rubbers are present in the body of pellets and polypropylene fibers are distributed homogeneously. Polypropylene fibers reaching outside the pellet will adhere with the matrix zone of concrete, which is expected to contribute to the strength of concrete specimens. Also, pellets were formed as a single core which provides increasing strength value until failure of pellets. This is an advantage against multilayered pellets because aggregates will work monolithic and crushing strength will be greater.

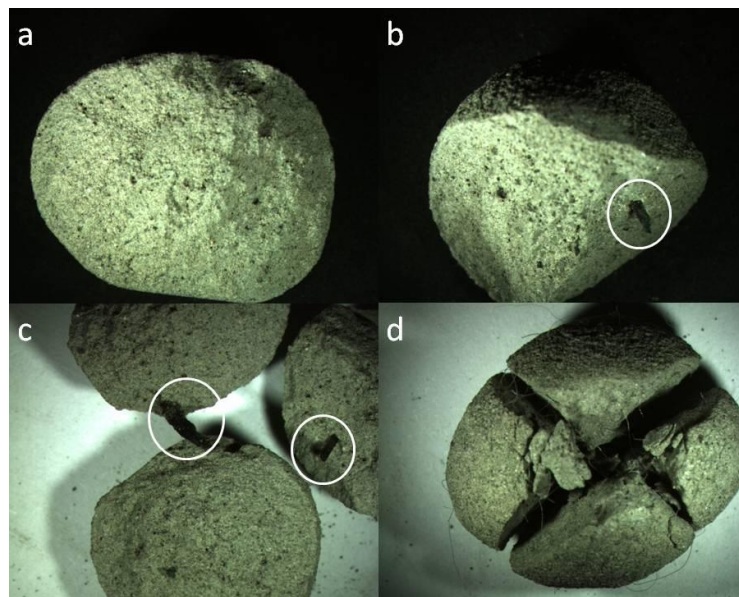


Figure 4.1. Microscopic observation of crushed pellets, (a) LC, (b) L1P, (c) L5P, (d) L1F.

#### 4.2. Fresh Concrete Properties

All concrete mixes were cast by using a high range water reducing agent at required dosage for achieving a slump of  $14 \pm 2$ . The LWACs were workable and cohesive and segregation was not observed. Fresh concrete properties are presented in Table 4.3.

When any type of LWAs were replaced with normalweight aggregate at volume fraction of 50% of coarse aggregate volume, unit weight decreased and air content increased. However, when natural coarse aggregate was replaced fully with lightweight fly ash aggregates, there was a significant reduction in the density of fresh concretes. Besides, when tire chips were used instead of coarse aggregates in any series of production plan,

unit weight decreased and air content increased drastically. Using tire chips also caused shear slump as seen in Figure 4.2. This makes use of tire chips questionable in regards of workability.

Table 4.3. Properties of fresh concrete.

Production Plan	Mix 1(22 dm <sup>3</sup> )*			Mix 2(26 dm <sup>3</sup> )**		
	Unit Weight (kg/m <sup>3</sup> )	Slump (cm)	Air Content (%)	Unit Weight (kg/m <sup>3</sup> )	Slump (cm)	Air Content (%)
CCSt(4-16mm)	2440	12.5	0.51	2410	14	1.58
CSt(4-8mm)TC(8-16mm)	1740	16(Shear)	18.29	1800	15(Shear)	15.37
<b>LC(4-8mm)CSt(8-16mm)</b>	2210	16	1.58	2230	14.5	1.58
<b>LC(8-16)CSt(4-8)</b>	2179	14.5	2.59	2200	15	1.58
<b>LC(4-8 and 8-16)</b>	1970	16	3.56	1980	16	3.53
L1P(4-8mm)CSt(8-16mm)	2230	14	1.58	2230	14.5	1.57
L1P(8-16)CSt(4-8)	2180	14	2.61	2200	14	1.57
L1P(4-8 and 8-16)	2000	15.5	2.62	1970	15	3.51
<b>L5P(4-8mm)CSt(8-16mm)</b>	2214	15	1.58	2210	15	1.57
<b>L5P(8-16)CSt(4-8)</b>	2180	14.5	2.61	2160	14	3.52
<b>L5P(4-8 and 8-16)</b>	1990	15	2.62	1970	15	3.51
L1F(4-8mm)CSt(8-16mm)	2220	14.5	1.58	2230	15	1.82
L1F(8-16)CSt(4-8)	2200	14	1.58	2180	13.5	2.60
L1F(4-8 and 8-16)	2000	16	1.58	2000	16	1.77
<b>LC(4-8mm)TC(8-16mm)</b>	1660	16(Shear)	14.37	1600	15(Shear)	17.35
<b>L1P(4-8mm)TC(8-16mm)</b>	1650	14.5(Shear)	14.38	1600	15(Shear)	17.35
<b>L5P(4-8mm)TC(8-16mm)</b>	1630	15.5(Shear)	16.34	1610	16(Shear)	16.33
<b>L1F(4-8mm)TC(8-16mm)</b>	1590	16(Shear)	18.30	1510	15(Shear)	21.77

\* For (Impact Test, Pull-Out Test)

\*\* For (Comp. Test, Splitting Tensile Test, Fracture Toughness Test)



Figure 4.2. Shear slump occurring in fresh concrete with tire chips.

### 4.3. Hardened Concrete Properties

#### 4.3.1. Compressive Strength and Modulus of Elasticity

Compressive strength and modulus of elasticity of concrete specimens produced with crushed stone as normalweight coarse aggregate were the highest in all production series since the cold-bonded lightweight fly ash aggregate was weaker than the mortar phase and normalweight coarse aggregate. A similar behavior was also indicated by Yang [112], Gesoğlu [6] and Kockal [38].

As it was expected, when concrete mixtures consisted of both LWA and crushed stone as normalweight coarse aggregate in the same volume fraction compressive strength and modulus of elasticity values of concrete specimens were obtained slightly lower than those of concrete specimens produced with normal weight coarse aggregate. The use of LWAs as a substitute of crushed stone in total volume fraction of coarse aggregate gave rise to a considerable decrease of compressive strength and modulus of elasticity of concrete specimens due to the higher porosity and lower strength of the lightweight aggregates. When LWAs in the size of 4-8mm and tire chips (8-16mm) were used as coarse aggregate drastic drop was observed in compressive strength and modulus of elasticity values. However, while only crush stone (4-8mm) replaced fully with LWAs (4-8mm) in the same series, compressive strength and modulus of elasticity were obtained slightly higher as it is seen in Figure 4.3 and 4.4.

The overall compressive strength changed from 49.0 to 29.8 MPa when crushed stone was replaced completely with LWA as coarse aggregate. While 50% LWA and 50% tire chips were used as coarse aggregate, compressive strength of lightweight rubberized concrete further reduced to 6.8 MPa. This trend was also reported in some studies. According to the study conducted by Gesoglu *et al.* [76], when cold-bonded lightweight fly ash aggregate volume in concrete with w/c ratio of 0.35 increased compressive strength of LWAC decreased from 40.1 to 29.1 MPa. Besides, when w/c ratio was increased to 0.55, compressive strength of LWAC decreased from 23.2 to 20.8 MPa. With respect to the study performed by Güneyisi *et al.* [79], concrete containing natural sand and crushed limestone as fine and coarse aggregate respectively with “0” % rubber content and w/c

ratio of 0.40, had a compressive strength of 75.8 MPa. However, while rubber content (crumb rubber and tire chips in equal volume instead of fine and coarse aggregate respectively) increased to 50% by total aggregate volume with the same w/c ratio, compressive strength of rubberized concrete specimen drastically decreased to 10.5 MPa.

For various production series, the relations between compressive strength values can be summarized as follows:

- $L1P(4-8mm)CSt(8-16mm) > L5P(4-8mm)CSt(8-16mm) > LC(4-8mm)CSt(8-16mm) > L1F(4-8mm)CSt(8-16mm)$
- $L1P(8-16mm)CSt(4-8mm) > LC(8-16mm)CSt(4-8mm) > L1F(8-16mm)CSt(4-8mm) > L5P(8-16mm)CSt(4-8mm)$
- $L1P(4-16mm) > L1F(4-16mm) > LC(4-16mm) > L5P(4-16mm)$
- $CSt(4-8mm)TC(8-16mm) > L5P(4-8mm)TC(8-16mm) > L1P(4-8mm)TC(8-16mm) = LC(4-8mm)TC(8-16mm) > L1F(4-8mm)TC(8-16mm)$

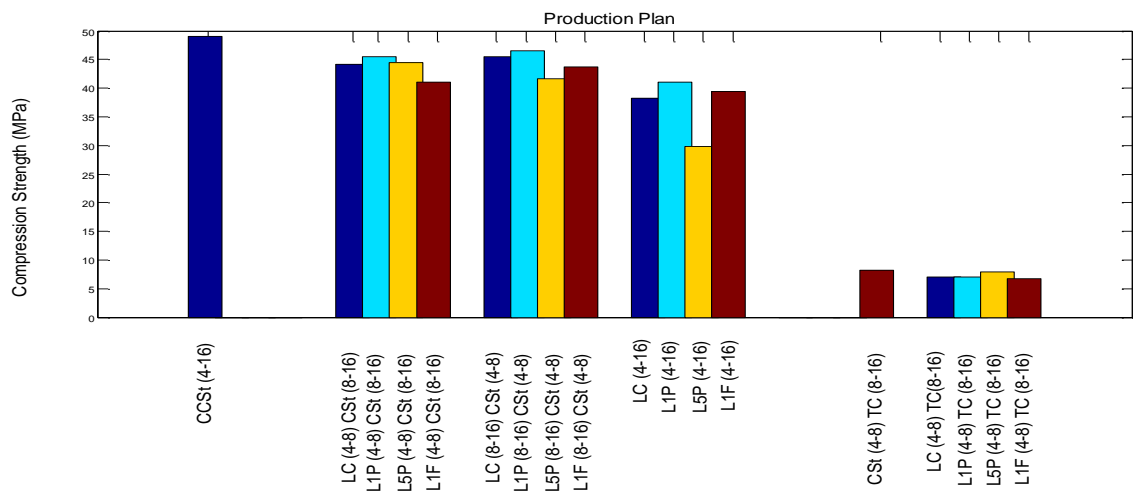


Figure 4.3. Compressive strength values for all series, grouped by aggregate type.

On the other hand, the overall modulus of elasticity changed from 25.7 to 19.7 GPa when crushed stone was replaced completely with LWA as coarse aggregate. While 50% LWA and 50% tire chips were used as coarse aggregate, modulus of elasticity of lightweight rubberized concrete further reduced to 6.5 GPa. This trend was also reported in

some studies. According to the study conducted by Gesoglu *et al.* [76], when cold-bonded lightweight fly ash aggregate volume in concrete with w/c ratio of 0.35 was increased, modulus of elasticity of LWAC decreased from 22.4 to 18.2 GPa. Besides, when w/c ratio was increased to 0.55, modulus of elasticity of LWAC decreased from 19.1 to 14.2 GPa. With respect to the study performed by Güneyisi *at al.* [79], concrete containing natural sand and crushed limestone as fine and coarse aggregate respectively with “0” % rubber content and w/c ratio of 0.40, had an elastic modulus of 45.9 GPa. However, while rubber content (crumb rubber and tire chips in equal volume instead of fine and coarse aggregate respectively) increased to 50% by total aggregate volume with the same w/c ratio, modulus of elasticity of rubberized concrete specimen drastically decreased to 7.6 GPa.

For various production series, the relations between modulus of elasticity values can be summarized as follows:

- L5P(4-8mm)CSt(8-16mm) > L1P(4-8mm)CSt(8-16mm) ≥ LC(4-8mm)CSt(8-16mm) > L1F(4-8mm)CSt(8-16mm)
- L1P(8-16mm)CSt(4-8mm) > LC(8-16mm)CSt(4-8mm) > L1F(8-16mm)CSt(4-8mm) > L5P(8-16mm)CSt(4-8mm)
- LC(4-16mm) > L1P(4-16mm) > L1F(4-16mm) > L5P(4-16mm)
- CSt(4-8mm)TC(8-16) > LC(4-8mm)TC(8-16mm) > L5P(4-8mm)TC(8-16mm) > L1P(4-8mm)TC(8-16mm) > L1F(4-8mm)TC(8-16mm)

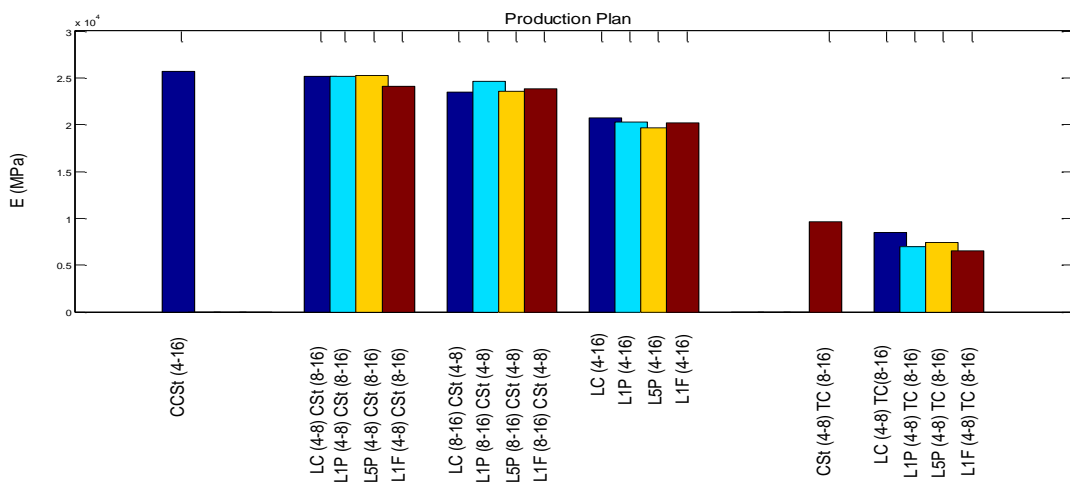


Figure 4.4. Elastic modulus values for all series, grouped by aggregate type.

As it is seen in Figure 4.5, the compressive strength values for concrete specimens produced with LWAs (4-8 mm) and crush stone (8-16 mm) as coarse aggregates were generally lower than that of concrete specimens produced with LWAs (8-16 mm) and crush stone (4-8 mm). When LWAs completely replaced with crushed stone as coarse aggregates the compressive strength of concretes further decreased. The use of tire chips on the other hand drastically decreases the compressive strength of all series.

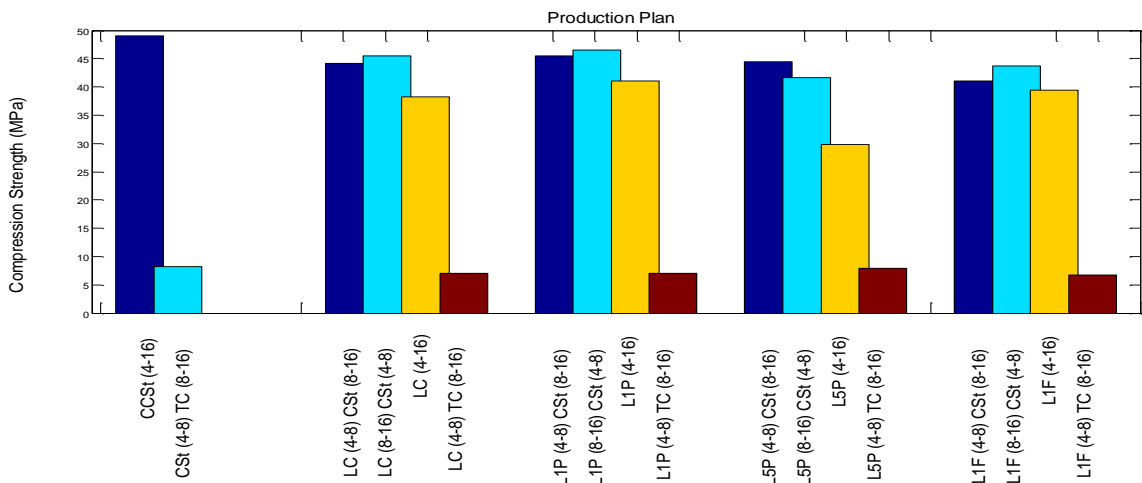


Figure 4.5. Compressive strength values for all series, grouped by aggregate size.

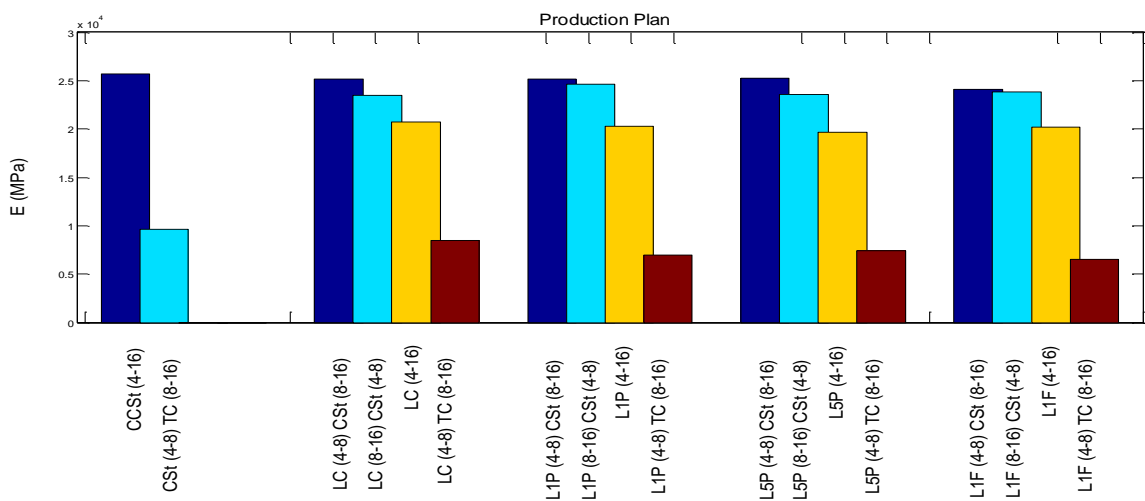


Figure 4.6. Elastic modulus values for all series, grouped by aggregate size.

The modulus of elasticity values for concrete specimens produced with LWAs (4-8 mm) and crush stone (8-16 mm) as coarse aggregates were higher than that of concrete specimens produced with LWAs (8-16 mm) and crush stone (4-8 mm) as it is seen in Figure 4.6. When LWAs were completely used as coarse aggregate the modulus of elasticity further decreased. The use of tire chips on the other hand drastically decreases modulus of elasticity of all series.

### 4.3.2. Splitting Tensile Strength

The average splitting tensile strength of concrete specimens CCSt(4-16mm) produced with crushed stone as normal weight coarse aggregate was the highest in all production series.

When concrete mixtures consisted of both LWA and crushed stone as normalweight coarse aggregate in the same volume fraction splitting tensile strength values of concrete specimens were slightly lower than those of concrete specimens produced with normalweight coarse aggregate. The use of LWAs as a substitute of crushed stone in total volume fraction of coarse aggregate gave rise to a considerable decrease of splitting tensile strength of concrete specimens. When in the size of 4-8mm LWAs and 8-16mm tire chips were used as coarse aggregate drastic drop was observed in splitting tensile strength values. However, splitting tensile strength for the series of CSt(4-8)TC(8-16) were slightly higher than that of concrete specimens with tire chips and LWAs (4-8mm) instead of crush stone (4-8mm) as it is seen in Figure 4.7 and 4.8.

The overall splitting tensile strength changed from 4.71 to 2.82 MPa when crushed stone was replaced completely with LWA as coarse aggregate. While 50% LWA and 50% tire chips were used as coarse aggregate, splitting tensile strength of lightweight rubberized concrete further reduced to 1.16 MPa. This trend was also reported in some studies. According to the study conducted by Gesoglu *et al.* [76], when cold-bonded lightweight fly ash aggregate volume in concrete with w/c ratio of 0.35 was increased, splitting tensile strength of LWAC decreased from 3.22 to 2.58 MPa. Besides, when w/c ratio was increased to 0.55, splitting tensile strength of LWAC decreased from 2.35 to 1.86 MPa. With respect to the study performed by Güneyisi *et al.* [79], concrete containing natural

sand and crushed limestone as fine and coarse aggregate respectively with “0” % rubber content and w/c ratio of 0.40, had a splitting tensile strength of 4.1 MPa. However, while rubber content (crumb rubber and tire chips in equal volume instead of fine and coarse aggregate respectively) increased to 50% by total aggregate volume with the same w/c ratio, splitting tensile strength of rubberized concrete specimen drastically decreased to 0.9 MPa.

For various production series, the relations between splitting tensile strength values can be summarized as follows:

- $LC(4-8mm)CSt(8-16mm) > L1F(4-8mm)CSt(8-16mm) \geq L5P(4-8mm)CSt(8-16mm) > L1P(4-8mm)CSt(8-16mm)$
- $L5P(8-16mm)CSt(4-8mm) > L1F(8-16mm)CSt(4-8mm) > LC(8-16mm)CSt(4-8mm) > L5P(8-16mm)CSt(4-8mm)$
- $L5P(4-16mm) > LC(4-16mm) > L1F(4-16mm) \geq L1P(4-16mm)$
- $CSt(4-8mm)TC(8-16mm) > L5P(4-8mm)TC(8-16mm) > L1P(4-8mm)TC(8-16mm) \geq LC(4-8mm)TC(8-16mm) > L1F(4-8mm)TC(8-16mm)$

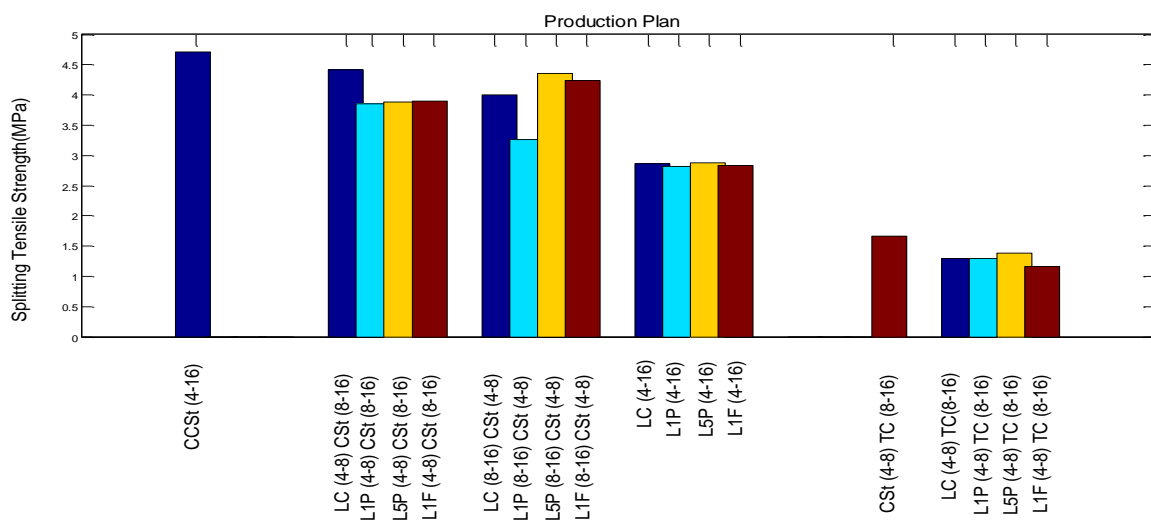


Figure 4.7. Splitting tensile strength values for all series, grouped by aggregate type.

For various production series, the relations between splitting tensile strength values can be summarized as follows:

- $LC(4-8mm)CSt(8-16mm) > LC(8-16mm)CSt(4-8mm) > LC(4-16mm) > LC(4-8mm)TC(8-16mm)$
- $L1P(4-8mm)CSt(8-16mm) > L1P(8-16mm)CSt(4-8mm) > L1P(4-16mm) > L1P(4-8mm)TC(8-16mm)$
- $L5P(8-16mm)CSt(4-8mm) > L5P(4-8mm)CSt(8-16mm) > L5P(4-16mm) > L5P(4-8mm)TC(8-16mm)$
- $L1F(8-16mm)CSt(4-8mm) > L1F(4-8mm)CSt(8-16mm) > L1F(4-16mm) > L1F(4-8mm)TC(8-16mm)$

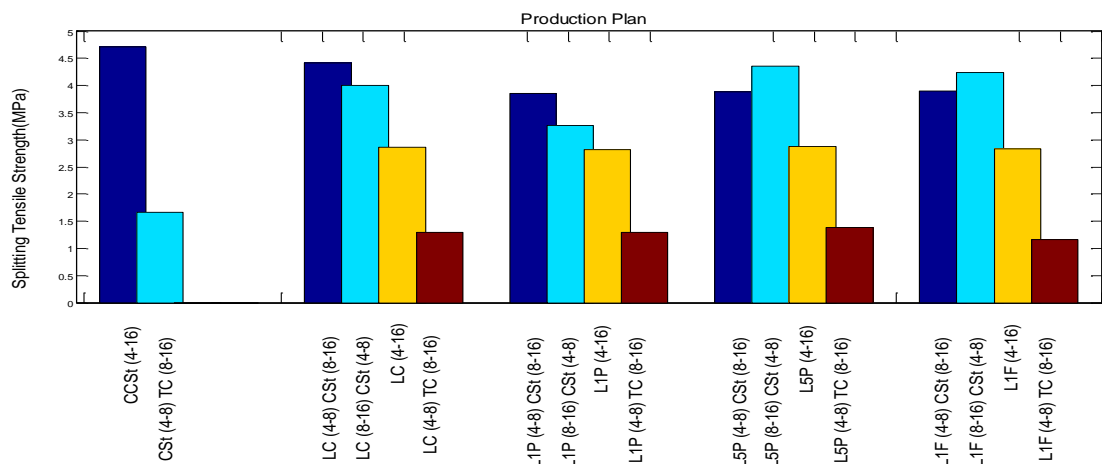


Figure 4.8. Splitting tensile strength values for all series, grouped by aggregate size.



Figure 4.9. Splitting section view of specimens with LWA(4-8mm) and tire chips(8-16mm) as coarse aggregate.

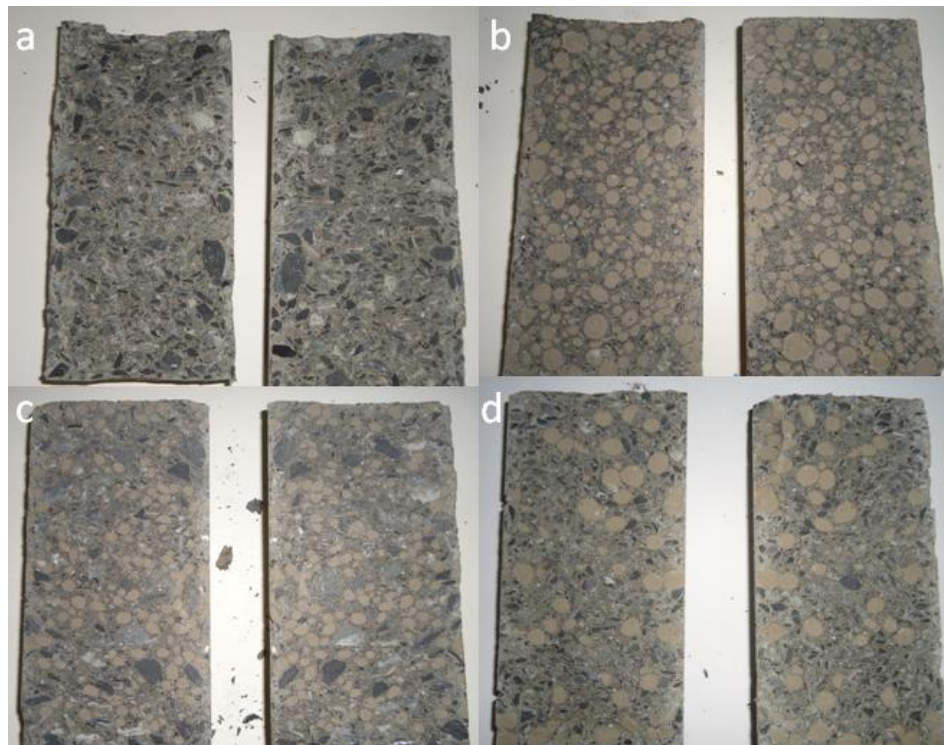


Figure 4.10. Splitting section view of specimens with (a) crushed stone, (b) LWA, (c) LWA(4-8mm) and crushed stone(8-16mm), (d) crushed stone(4-8mm) and LWA(8-16mm), as coarse aggregate.

### 4.3.3. Failure Impact Energy

Average failure impact energy of concrete specimens produced with crushed stone as normalweight coarse aggregate was the highest in all production series due to the lower porosity and higher strength of the normalweight aggregates and so concrete specimen. Contrary to the results of the study carried out by Topcu and Avcular [31], addition of tire chips (8-16mm) as coarse aggregate into the concrete mixture with crushed stone in the size of 4-8mm as the other half of coarse aggregate by volume did not increase the energy absorbing capacity and the average failure impact energy above the concrete with full use of crushed stone as coarse aggregate, but almost reached to it.

Addition of tire chips (8-16mm) as coarse aggregate into the concrete mixture with LWAs in the size of 4-8mm as the other half of coarse aggregate by volume generally ended up with an increase in energy absorbing capacity and so average failure impact energy compared to the use of LWAs in total volume fraction of coarse aggregate. Besides,

when the concrete specimens with different LWAs in the size of 4-16mm as coarse aggregates are compared to each other, it is obviously seen in Figure 4.11 that average failure impact energy of L1F(4-16) type concrete specimen is the highest(4036 kN mm) that may be attributed to the extra adherence between polypropylene fiber reinforced pellets and matrix phase by the help of polypropylene fibers existing on the surface of aggregates.

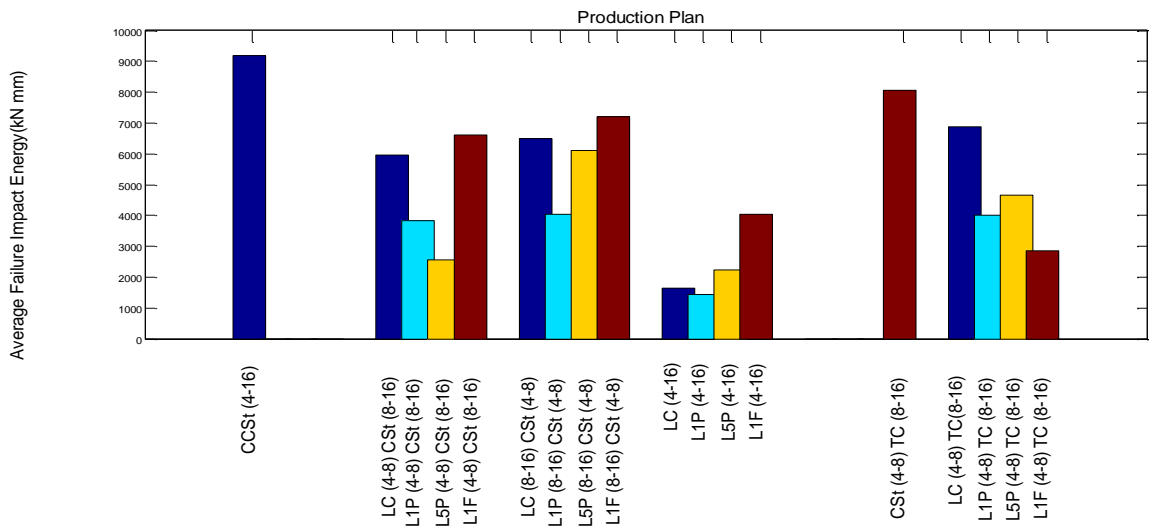


Figure 4.11. Average failure impact energy values for all series, grouped by aggregate type.

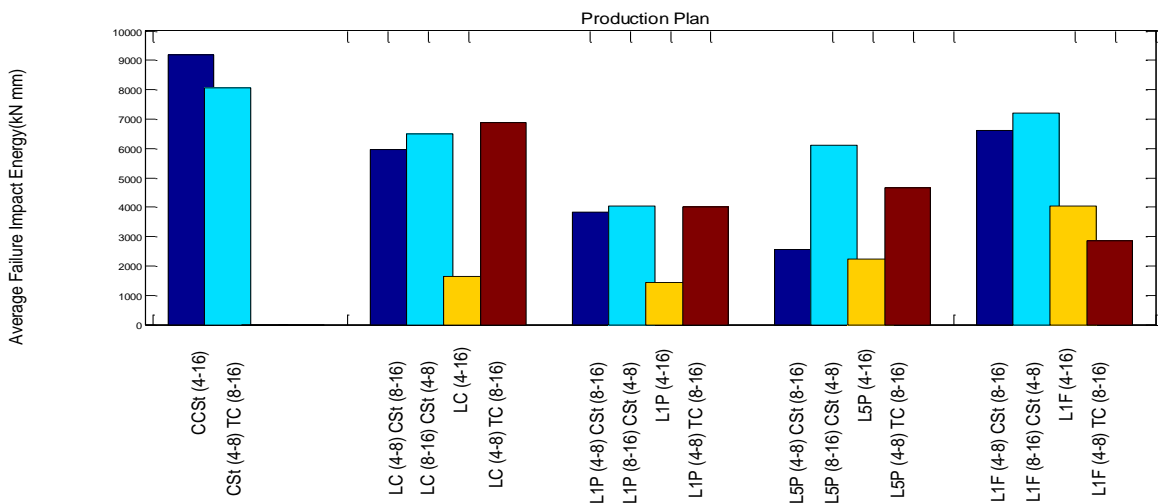


Figure 4.12. Average failure impact energy values for all series, grouped by aggregate size.

The overall failure impact energy changed from 9183 to 1434 kN mm when crushed stone was replaced completely with LWA as coarse aggregate. While 50% LWA and 50% tire chips were used as coarse aggregate, failure impact energy of lightweight rubberized concrete LC(4-8)TC(8-16) increased to 6879 kN mm that is closed to the maximum value of 7215 kN mm of the series containing both LWA and crushed stone equally as coarse aggregate by volume. Besides, the average failure impact energy of concrete series CSt(4-8)TC(8-16) was 8053 kN mm that was the highest in the concrete series containing tire chips as coarse aggregate.

#### **4.3.4. Steel-Concrete Bond Strength**

The combination of adhesion, friction and support of the ribs in deformed steel provides the bond between steel and the concrete. The steel is extracted from the confining concrete matrix against bonding as the load is increased. The adhesion mechanism is enabled at first when the load was applied. While the adhesion is active, steel remains bonded to the concrete and no slip occurs. Friction and rib support get started after adhesion has failed and this leads to relative movements between concrete and steel. Herein, remarkable slip may be observed as the cracks were formed and grown. In this part of study, the pullout tests were carried out by recording the load and loaded end slip data for each test till failure. At the end of experimental study, the average ultimate bond strength through deformed steel bar and bond strength occurred at 0.25, 0.50 and 1.00 mm loaded end slip for each test were calculated in conformity with ASTM C234 [110]. The relevant results for different production series are exhibited in Table C.5.

All tests were conducted at proper loading speed until the maximum load value had been reached without any yielding of steel bars. During this process, concrete specimens of all series without tire chips as coarse aggregate split when the load reached to the ultimate value; however the remaining group of series which contained tire chips showed longitudinal cracks without splitting.

When LWAs were used in total volume fraction of coarse aggregate ultimate bond strength slightly decreased from 11.44 MPa for CCSt84-16) to 8.52 MPa like a similar behavior reported by Gesoğlu [6] that a gradual decrease in ultimate bond strength was

observed with the increase in volume percent of lightweight aggregate. However, when LWA and crushed stone were used together in an equal part as coarse aggregate by volume, ultimate bond strength increased without any trend. For instance, L1F(4-8)CS(8-16) series showed an increase to 16.11 MPa in ultimate bond strength that may be attributed to the extra adherence between polypropylene fiber reinforced pellets and matrix phase that prevents possible cracking by the help of polypropylene fibers existing on the surface of aggregates. Besides, the ultimate bond strength values of rubberized concrete with tire chips were lower than that of plain concrete. This is accounted firstly for the adherence problem existing between tire chips and matrix zone of cold bonded pellets and secondly for the extra void entrapped by crumb rubber.

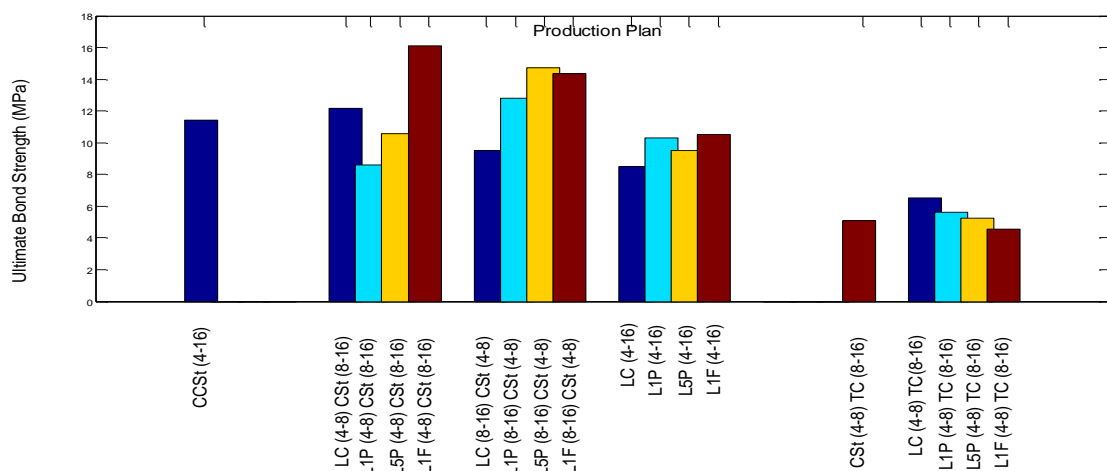


Figure 4.13. Ultimate bond strength values for all series, grouped by aggregate type.

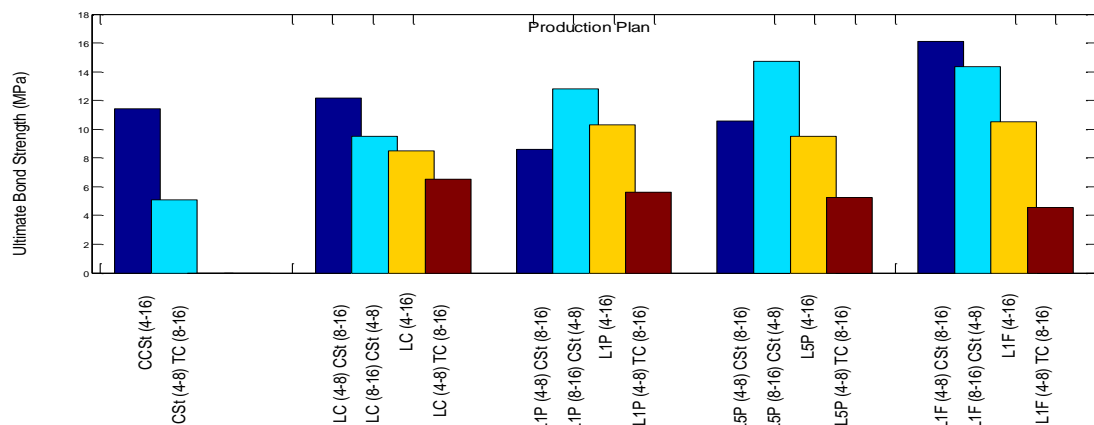


Figure 4.14. Ultimate bond strength values for all series, grouped by aggregate size.

As opposed to the ultimate bond strength, the use of LWAs both in equal volume with crushed stone and fully use as coarse aggregate in concrete mixes slightly increased the nominal bond strength from 5.06 MPa for CCSt(4-16) to 7.08 MPa and 6.12 MPa respectively at 1.00 mm loaded end slip. This positive contribution of LWAs may be accounted for a better coherence and interlocking of the LWA with the surrounding concrete that minimize the cracking and so utilize the adhesion between the concrete and rebar [6, 97]. This case was opposite for rubberized concrete. There existed an adhesion loss between aggregates and cement paste due to the presence of tire chips and that caused a decrease in nominal bond strength values of rubberized concretes to 2.33 MPa as seen in Figure 4.15.

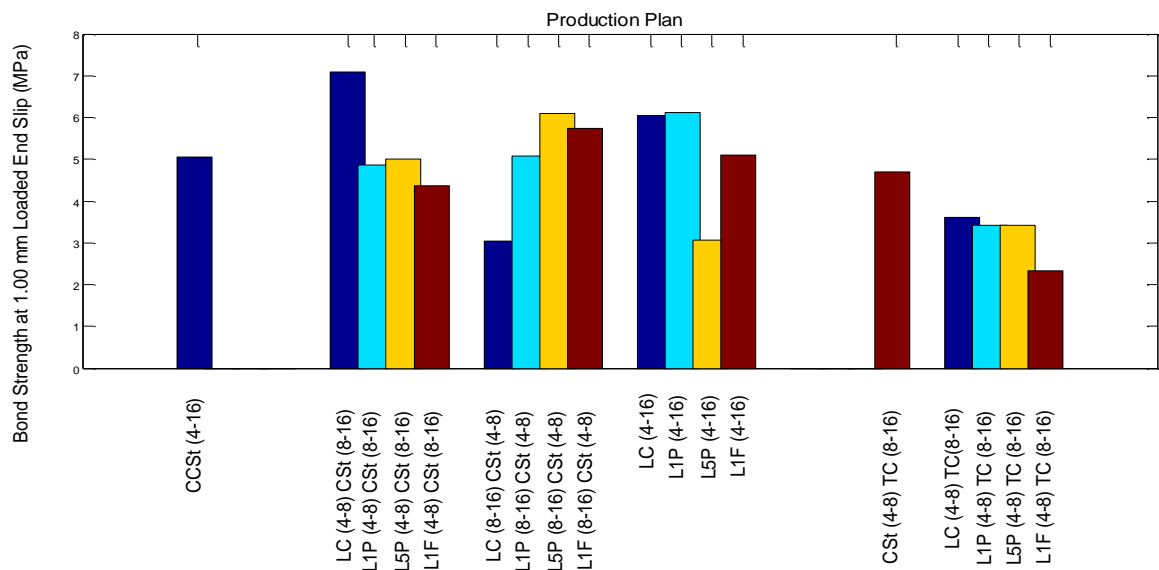


Figure 4.15. Bond strength values at 1.00 mm loaded end slip for all series, grouped by aggregate type.

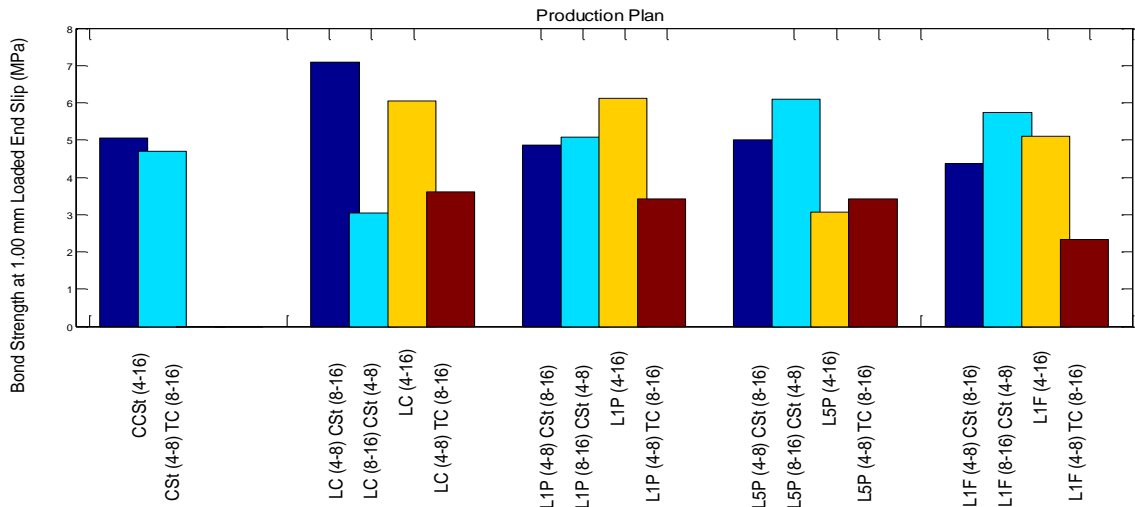


Figure 4.16. Bond strength values at 1.00 mm loaded end slip for all series, grouped by aggregate size.

#### 4.3.5. Flexural Strength and Toughness

Flexural tests were performed on beam specimens with dimensions of 100x100x500 mm under three point loading by using MTS loading machine. Test procedure was given in chapter 3. Three beams for each series were tested until failure. The maximum load and displacement were recorded. Finally, the average values of flexural strength and toughness were calculated by using these data. The results are shown in Table C.6 and Table C.7.

Addition of LWAs in the size of 4-8mm as coarse aggregate into the concrete mixture with crushed stone(8-16mm) as the other half of coarse aggregate by volume ended up with a decrease in flexural strength from 9.38 to 6.42 MPa compared to that of concrete with full of crushed stone as coarse aggregate. When LWAs were used in total volume fraction of coarse aggregate flexural strength of concrete specimens further decreased to 4.69 MPa. Finally, the use of tire chips (8-16mm) as coarse aggregate in the concrete mixtures mixture with LWAs in the size of 4-8mm as the other half of coarse aggregate by volume resulted in a drastic decrease of flexural strength to 3.05 MPa as seen in Figure 4.17 and Figure 4.18. Decrease in flexural strength may be attributed to the strength loss due to the addition of lightweight aggregates and tire chips into the concrete mixtures as indicated by a previous study of Liu *et al.* [25]. In that study, although the use of tire rubber as aggregate with replacing ratio up to 10% in concrete ended up with

significant enhancement in the flexural strength of concrete as a result of increasing energy absorbing capacity and elasticity characteristic of concrete, the ratio of rubber content more than 10% concluded with a decrease in flexural strength.

According to the study conducted by Turatsinze and Garros [93], increasing the rubber content caused a reduction of the load bearing capacity and flexural stiffness that were correlated with compressive strength drop and low modulus of elasticity respectively. In contrast to that, significant strain capacity gain was recorded due to the presence of rubber aggregates that prevent the proceeding of microcracks and hence delaying their incorporation.

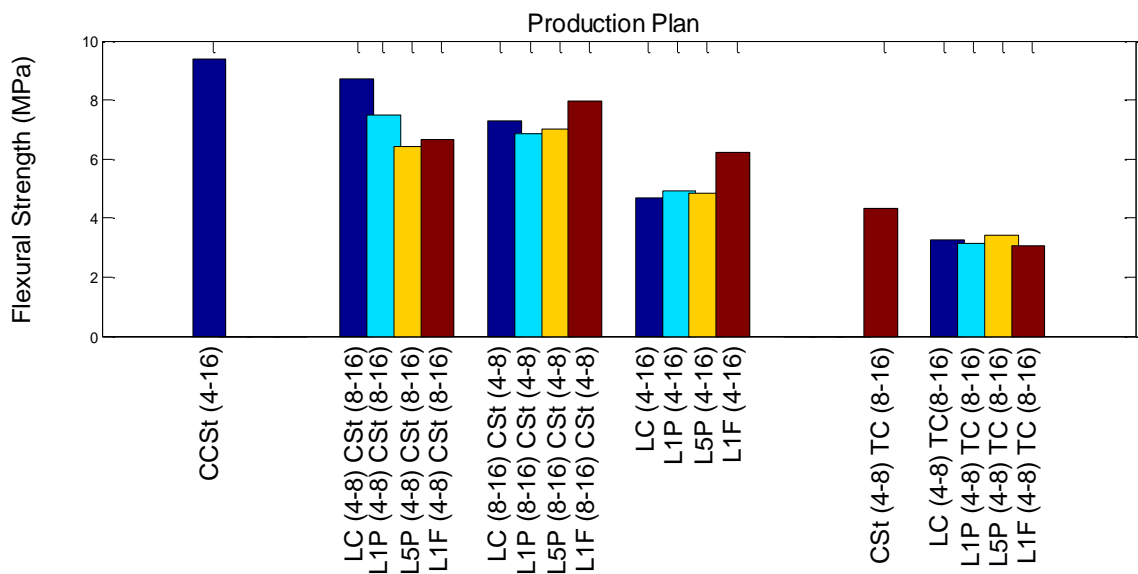


Figure 4.17. Flexural strength values for all series, grouped by aggregate type.

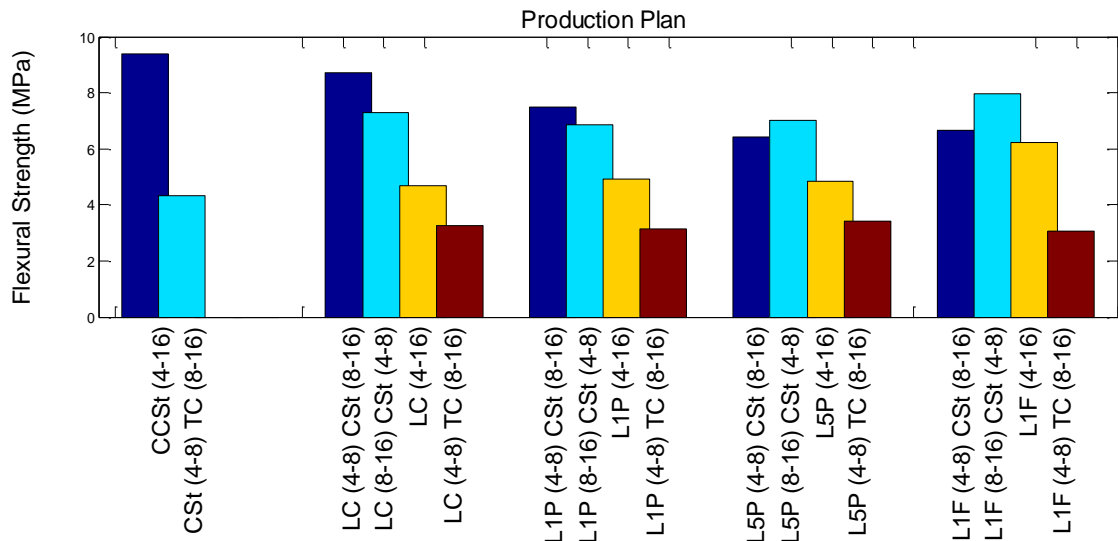


Figure 4.18. Flexural strength values for all series, grouped by aggregate size.

The toughness of plain and fiber-reinforced concrete can be regarded as their energy absorption capacity, which is the area under the load-deflection curve obtained during a flexure test. In this study, fracture toughness value of concrete specimens produced with only natural-normalweight aggregate was the highest. Any replacement of LWA or tire chips with normalweight coarse aggregate decreased the toughness due to the strength loss. However, the use of tire chips with LWA in an equal part of coarse aggregate by volume had a positive effect to increase toughness compared to full use of LWA as coarse aggregate. This is accounted for the energy absorbing and crack arresting and bridging capacity of rubber chips. Khaloo *et al.* [87] also observed that concrete consisted of 25% rubber by volume fraction of total aggregate reached its ultimate toughness value. In excess of 25% of rubber content induced a decrease in toughness of rubberized concrete owing to strength loss.

The overall fracture toughness values changed from 3616 to 1070 N mm when crushed stone was replaced completely with LWA as coarse aggregate. However, while 50% LWA and 50% tire chips were used as coarse aggregate, fracture toughness of lightweight rubberized concrete L1P(4-8)TC(8-16) increased to 3046 N mm that is higher than the maximum value of 2700 N mm of the series containing both LWA and crushed stone equally as coarse aggregate by volume. Besides, the average fracture toughness of

concrete series CSt(4-8)TC(8-16) was 3055 N mm that was the highest in the concrete series containing tire chips as coarse aggregate. From this point of view, it can be concluded that tire chips addition could be more beneficial in favor of toughness and basic mechanical properties in case the optimum ratio is specified.

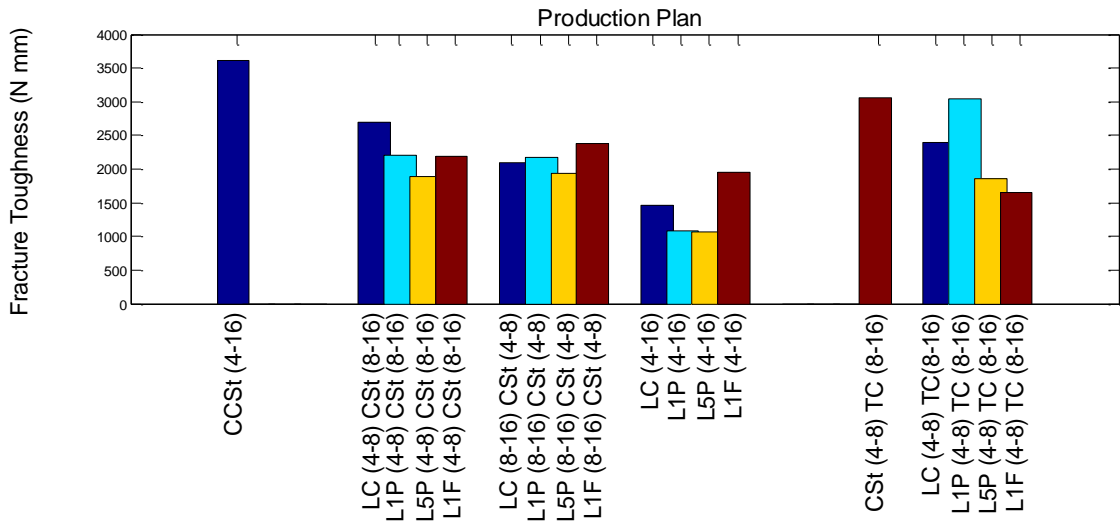


Figure 4.19. Fracture toughness values for all series, grouped by aggregate type.

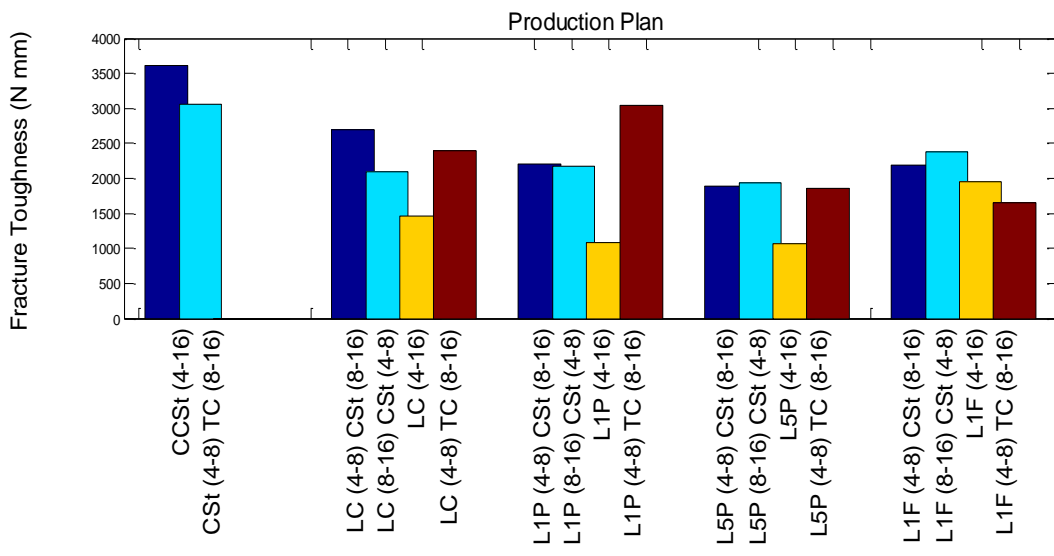


Figure 4.20. Fracture toughness values for all series, grouped by aggregate size.

## 5. SUMMARY AND CONCLUSIONS

An experimental programme was conducted to investigate some physical and mechanical properties of lightweight concretes made with cold bonded fiber reinforced fly ash pellets and also tire chips as coarse aggregates. Totally, 17 lightweight concrete mixtures were produced with lightweight aggregates ( LC, L1P, L5P and L1F) and tire chips at 0.40 w/c ratio and tested for compressive and splitting tensile strength, modulus of elasticity, failure impact energy, steel-concrete bond strength, three point bending/flexural strength and toughness. The results of experiments concluded the following:

Average unit weight and specific gravity values of LWAs were approximately 1.00 g/cm<sup>3</sup> and 1.60 respectively that are lower than those of normalweight aggregate due to porous structure of LWA, density of materials used to produce fly ash pellets, amounts of water used to obtain pellet formation and absence of any treatment of cold-bonded pellets such as water glass and slurry. These also apply to water absorption that was averagely 25% by weight.

Based on the crushing strength tests on individual LWAs, addition of crumb rubber into the pellets with the ratio of 0.1% (L1P) and 0.5% (L5P) increased crushing strength values from 3.78 MPa for LC to 4.19 and 3.90 MPa, respectively. This implies that in aggregate dimensions, crumb rubber addition not only increases impact strength but also crushing strength. This contradicts with the general view on compressive strength behavior of concrete specimens; which is tire chips addition to concrete decreases compressive strength. This may be accounted firstly for the adherence problem between tire chips and the matrix of lightweight concrete with cold bonded pellets, and secondly for the extra void entrapped by tire chips and thirdly for the difference in the failure mechanism in the fly ash pellets under point load and in concrete under compressive load. In this study average crushing strength values for L1F was slightly lower than that of LC. However, if we consider the standard deviation for the crushing strength values of LC and L1F, results are approximately the same.

According to optical microscopic observation, crumb rubbers are present in the body of pellets and polypropylene fibers are distributed homogeneously. Polypropylene fibers

reaching outside the pellet will adhere with the matrix zone of concrete, which is expected to contribute to the strength of concrete specimens. Also, pellets were formed as a single core which provides increasing strength value until failure of pellets. This is an advantage against multilayered pellets because aggregates will work monolithic and crushing strength will be greater.

When any type of LWAs were replaced with normalweight aggregate at volume fraction of 50% of coarse aggregate volume, unit weight decreased from 2440 kg/m<sup>3</sup> to 2179 kg/m<sup>3</sup> and air content increased from 0.51% to 1.58%. However, when natural coarse aggregate was replaced fully with lightweight fly ash aggregates, there was a significant reduction in the density of fresh concretes till the value of 1970 kg/m<sup>3</sup>. Besides, when tire chips were used instead of coarse aggregates in any series of production plan, unit weight decreased and air content increased drastically till the values of 1590 kg/m<sup>3</sup> and 18.30%, respectively. Using tire chips also caused shear slump that makes use of tire chips questionable in regards of workability.

The overall compressive strength changed from 49.0 to 29.8 MPa when crushed stone was replaced completely with LWA as coarse aggregate since the cold-bonded lightweight fly ash aggregate was weaker than the mortar phase and normalweight coarse aggregate. While 50% LWA and 50% tire chips were used as coarse aggregate, compressive strength of lightweight rubberized concrete further reduced to 6.8 MPa due to the higher porosity and strength loss. On the other hand, the overall modulus of elasticity changed from 25.7 to 19.7 GPa when crushed stone was replaced completely with LWA as coarse aggregate. While LWA and tire chips were used in an equal part as coarse aggregate by volume, modulus of elasticity of lightweight rubberized concrete further reduced to 6.5 GPa.

The overall splitting tensile strength changed from 4.71 to 2.82 MPa when crushed stone was replaced completely with LWA as coarse aggregate. However, when LWA and tire chips were used equally as coarse aggregate by volume, splitting tensile strength of lightweight rubberized concrete further reduced to 1.16 MPa.

Average failure impact energy of concrete specimens produced with crushed stone as normalweight coarse aggregate were the highest (9183 kN mm) in all production series due to the lower porosity and higher strength of the normalweight aggregates and so concrete specimen. Addition of tire chips (8-16mm) as coarse aggregate into the concrete mixture with LWAs in the size of 4-8mm as the other half of coarse aggregate by volume generally ended up with an increase in energy absorbing capacity and so average failure impact energy compared to the use of LWAs in total volume fraction of coarse aggregate. Besides, when the concrete specimens with different LWAs in the size of 4-16mm as coarse aggregates are compared to each other, average failure impact energy of L1F(4-16) type concrete specimens was the highest that may be attributed to the extra adherence between polypropylene fiber reinforced pellets and matrix phase by the help of polypropylene fibers existing on the surface of aggregates.

When LWAs were used in total volume fraction of coarse aggregate ultimate bond strength slightly decreased compared to normalweight concrete specimen from 11.44 MPa to 8.52 MPa. However, when LWA and crushed stone were used together in an equal part as coarse aggregate by volume, ultimate bond strength increased without any trend. For instance, L1F(4-8)CSt(8-16) series showed an increase in ultimate bond strength (16.11 MPa) that may be attributed to the extra adherence between polypropylene fiber reinforced pellets and matrix phase that prevents possible cracking by the help of polypropylene fibers existing on the surface of aggregates. Besides, the ultimate bond strength values (max: 6.54MPa, min: 4.57MPa) of rubberized concretes with tire chips were lower than that of plain concrete. This is accounted firstly for the adherence problem existing between tire chips and matrix zone of lightweight concrete with cold bonded pellets and secondly for the extra void entrapped by tire chips.

As opposed to the ultimate bond strength, the use of LWAs both in equal volume with crushed stone and fully use as coarse aggregate in concrete mixes slightly increased the nominal bond strength at 1.00 mm loaded end slip from 5.06 MPa(for plain concrete) to 7.05 and 6.12 MPa, respectively. This positive contribution of LWAs may be accounted for a better coherence and interlocking of the LWA with the surrounding concrete that minimize the cracking and so utilize the adhesion between the concrete and rebar. However, this case was opposite for rubberized concrete. There existed an adhesion loss

between aggregates and cement paste due to the presence of tire chips and that caused a decrease in nominal bond strength values of rubberized concretes (max: 3.60MPa, min: 2.33MPa).

Addition of LWAs in the size of 4-8mm as coarse aggregate into the concrete mixture with crushed stone(8-16mm) as the other half of coarse aggregate by volume ended up with a decrease in flexural strength compared to that of concrete with full of crushed stone as coarse aggregate from 9.89 MPa to 6.42 MPa. When LWAs were used in total volume fraction of coarse aggregate flexural strength of concrete specimens further decreased to 4.69 MPa. However, when the concrete specimens with different LWAs in the size of 4-16mm as coarse aggregates are compared to each other, it is seen that average flexural strength of L1F(4-16) type concrete specimens was the highest that may be attributed to the extra adherence between polypropylene fiber reinforced pellets and matrix phase by the help of polypropylene fibers existing on the surface of aggregates. Finally, the use of tire chips (8-16mm) as coarse aggregate in the concrete mixtures with LWAs in the size of 4-8mm as the other half of coarse aggregate by volume resulted in a drastic decrease of flexural strength down to 3.05 MPa. Decrease in flexural strength may be attributed to the strength loss due to the addition of lightweight aggregates and tire chips into the concrete mixtures. Although addition of tire chips caused a reduction of the load bearing capacity and flexural stiffness that were correlated with compressive strength drop and low modulus of elasticity respectively, significant strain capacity gain was recorded due to the presence of rubber chips as coarse aggregates that prevent the proceeding of microcracks and hence delaying their incorporation.

Fracture toughness value of concrete specimens (3616 N mm) produced with only natural normalweight aggregate was the highest. Any replacement of LWA with crushed stone decreased the toughness due to the strength loss. However, the use of tire chips with LWA in an equal part of coarse aggregate by volume had a positive effect to increase toughness compared to full use of LWA as coarse aggregate from averagely 1389 to 2240 N mm that is higher than the average value (2198 N mm) of concrete series with LWA and crushed stone equally as coarse aggregate by volume. This is accounted for the energy absorbing and crack arresting and bridging capacity of rubber chips.

As recommendations, the number of samples for each experiment have to be increased so as to get a trend to see the effect of different fibers (crumb rubber, polypropylene fiber and tire chips) into the cold-bonded lightweight pellets and concrete. Besides, it is a fact that impact resistance and toughness of concrete are increased with amount of tire chips. However, there may be a certain point that the mechanical properties of concrete such as compressive and splitting tensile strength, modulus of elasticity, bond strength and flexural strength started to decrease. Therefore, the optimum amount of tire chips should be determined for better analysis. Also, it is possible to use mineral admixture like silica fume with tire chips or crumb rubber instead of tire chips as fine aggregate to avoid from adherence problem and higher porosity and to have better workability. Moreover, further investigation regarding the effect of embedment length, diameter of rebar, concrete strength and loading pattern (static or dynamic) on steel-concrete bond behavior would be beneficial.

## APPENDIX A: EXPERIMENTAL TEST SETUPS



Figure A.1. Pelletization disc.



Figure A.2. Lightweight aggregate pelletization process.



Figure A.3. Crushing setup of an individual pellet.



Figure A.4. Drop-weight impact resistance test setup.

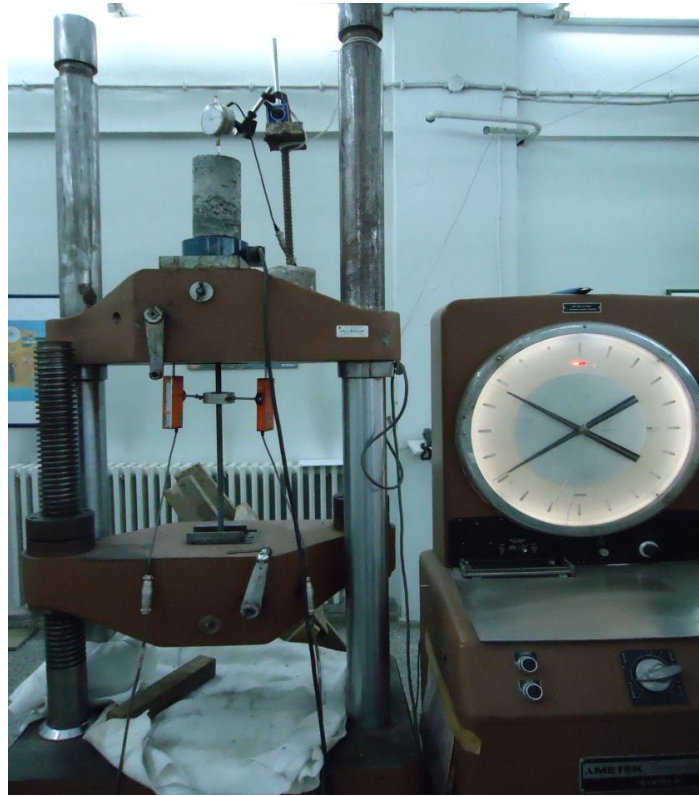


Figure A.5. Pullout test setup (Universal testing machine).



Figure A.6. Three point bending test setup.

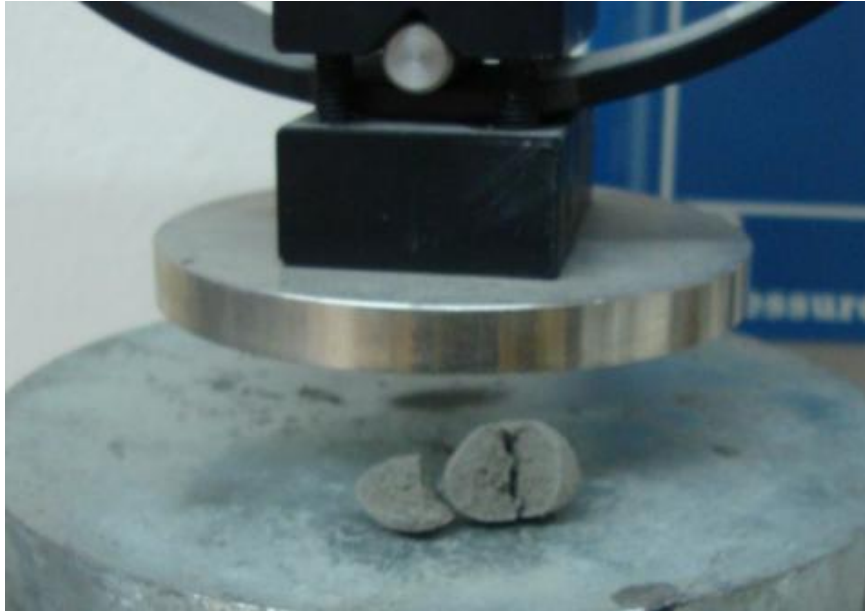
**APPENDIX B: FAILURE OF THE TEST SPECIMENS**

Figure B.1. Fracture behavior of a single pellet with or without crumb rubber.

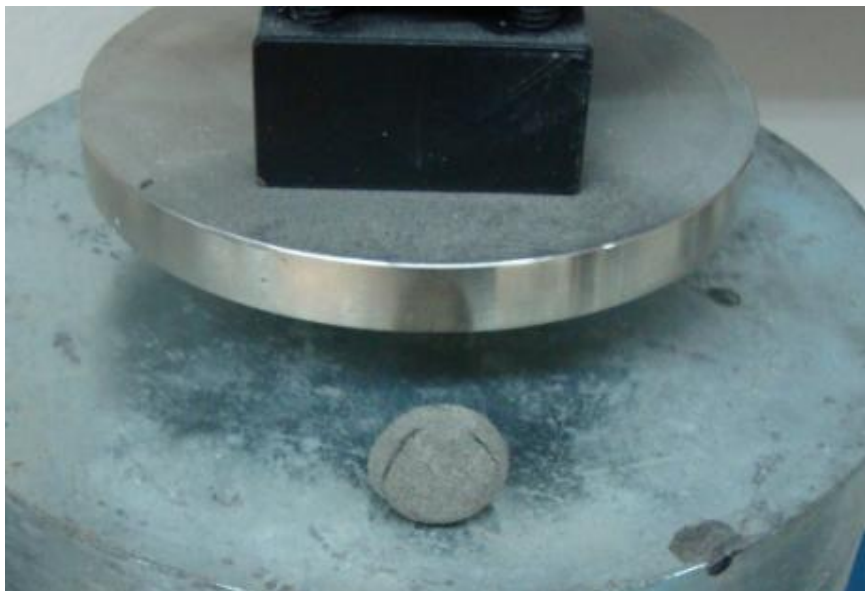


Figure B.2. Fracture behavior of a single pellet with polypropylene fiber.

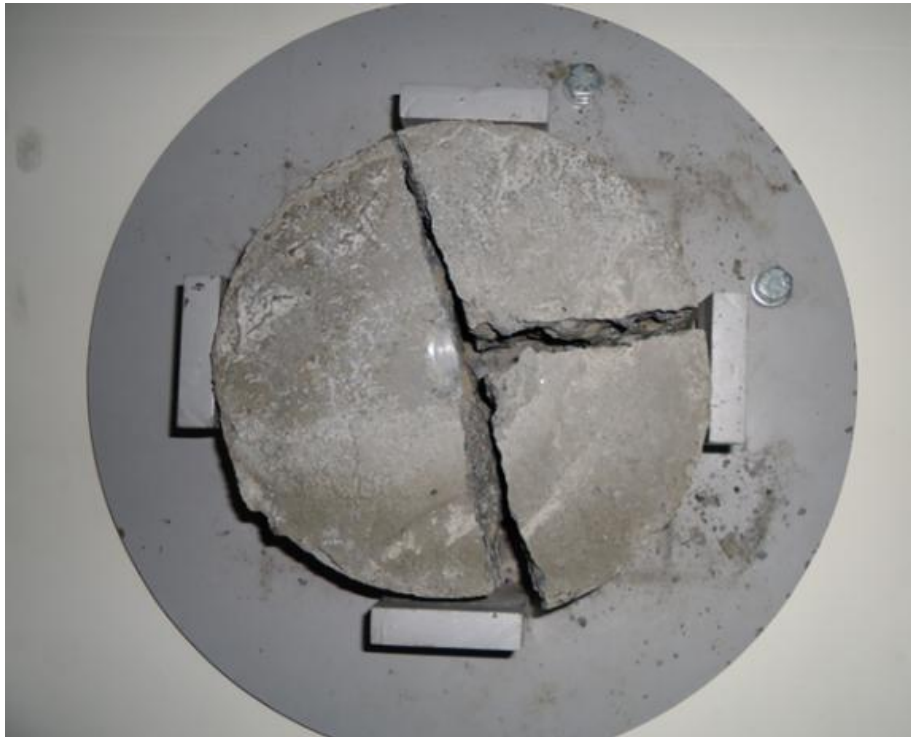


Figure B.3. Failure of impact resistance specimen without tire chips.

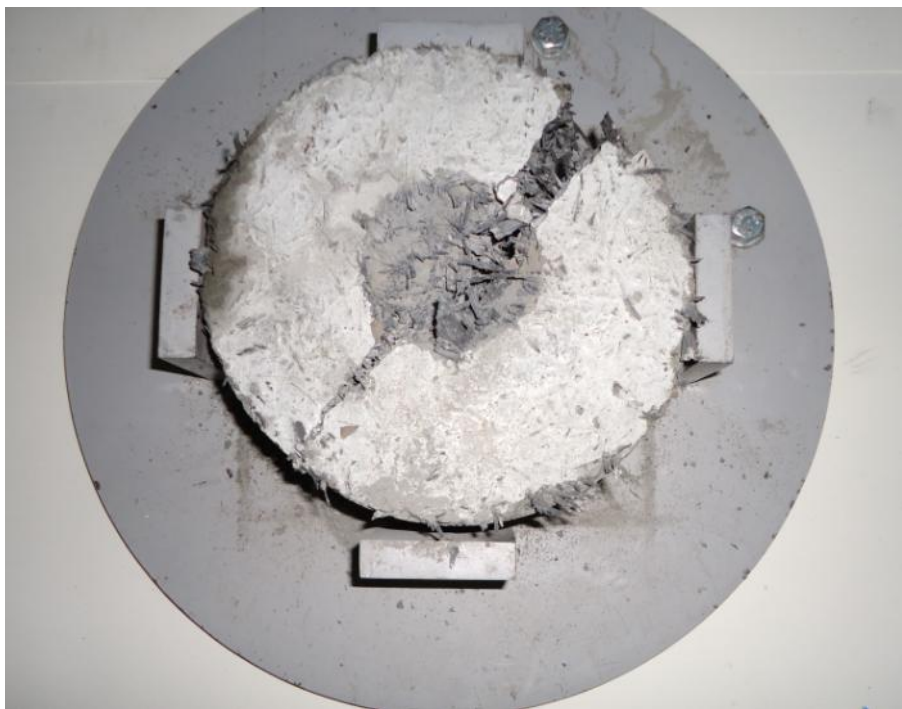


Figure B.4. Failure of impact resistance specimen with tire chips.



Figure B.5. Failure of pullout test specimen without tire chips.

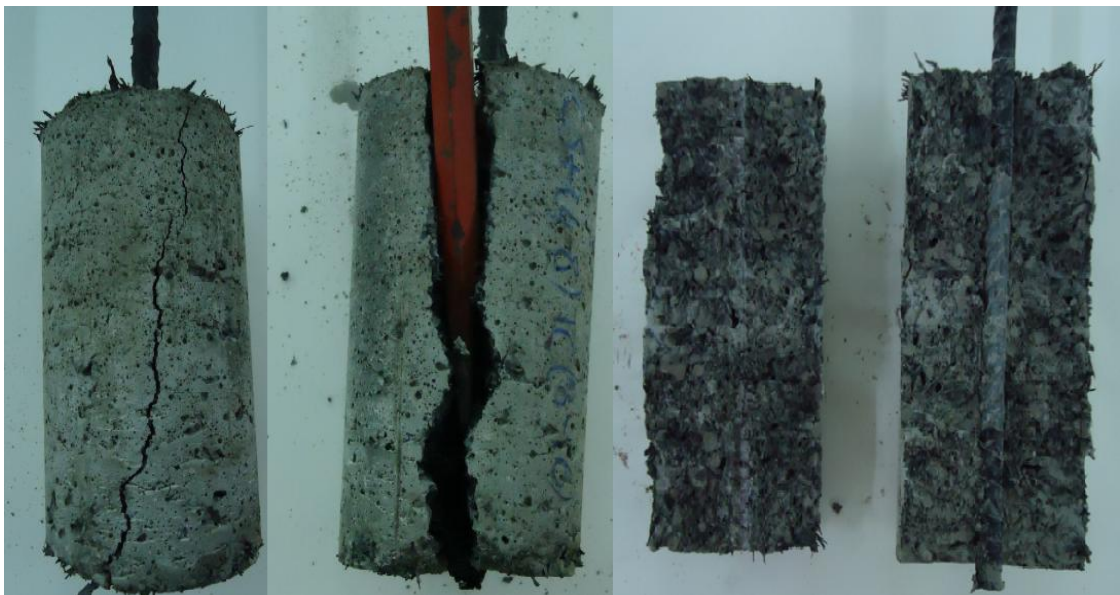


Figure B.6. Failure of pullout test specimen with tire chips.



Figure B.7. Failure of three point bending specimen without tire chips.



Figure B.8. Failure of three point bending specimen with tire chips.

## APPENDIX C: RESULT TABLES

Table C.1. Compressive Strength and Modulus of Elasticity (Pace Rate:2.40 kN/s).

					Average Values		
Production Plan	Specimen Number	Max Load (kN)	Strength (MPa)	E (Mpa)	Max Load (kN)	Strength (MPa)	E (Mpa)
CCSt(4-16mm)	1	389.4	49.58	26124	384.83	49.00	25679.67
	2	376.5	47.94	24921			
	3	388.6	49.48	25994			
CSt(4-8mm)TC(8-16mm)	1	79.1	10.07	9756.5	64.20	8.17	9597.97
	2	52.9	6.731	9578.2			
	3	60.6	7.711	9459.2			
LC(4-8mm)CSt(8-16mm)	1	364.09	46.36	25924	347.33	44.23	25183.00
	2	332.5	42.34	21662			
	3	345.4	43.98	27963			
LC(8-16)Cst(4-8)	1	358.7	45.67	23860	356.73	45.42	23432.33
	2	348.4	44.35	23424			
	3	363.1	46.24	23013			
LC(4-8 and 8-16)	1	309.7	39.43	22940	300.83	38.30	20750.00
	2	294.2	37.46	18143			
	3	298.6	38.02	21167			
L1P(4-8mm)CSt(8-16mm)	1	359.5	45.77	24126	357.63	45.54	25185.00
	2	347.9	44.3	26315			
	3	365.5	46.54	25114			
L1P(8-16)Cst(4-8)	1	353.9	45.06	27552	365.03	46.48	24642.33
	2	391.4	49.84	22629			
	3	349.8	44.54	23746			
L1P(4-8 and 8-16)	1	331.5	42.21	20350	322.73	41.09	20251.00
	2	320.2	40.77	19165			
	3	316.5	40.3	21238			
L5P(4-8mm)CSt(8-16mm)	1	353.5	45.01	26033	348.53	44.38	25268.33
	2	338.3	43.07	23583			
	3	353.8	45.05	26189			
L5P(8-16)Cst(4-8)	1	332.9	42.39	21559	327.13	41.65	23580.00
	2	352.1	44.83	24562			
	3	296.4	37.73	24619			
L5P(4-8 and 8-16)	1	238.6	30.37	18535	234.10	29.80	19688.67
	2	191	24.31	20829			
	3	272.7	34.72	19702			

Table C.1. Compressive Strength and Modulus of Elasticity (Pace Rate:2.40 kN/s) (cont.).

					Average Values		
Production Plan	Specimen Number	Max Load (kN)	Strength (MPa)	E (Mpa)	Max Load (kN)	Strength (MPa)	E (Mpa)
L1F(4-8mm)CSt(8-16mm)	1	324.6	42.33	19452	320.20	41.10	24141.33
	2	323.4	41.18	21175			
	3	312.6	39.8	31797			
L1F(8-16)Cst(4-8)	1	336.7	42.87	25364	343.10	43.69	23856.67
	2	346.1	44.07	20538			
	3	346.5	44.12	25668			
L1F(4-8 and 8-16)	1	328.7	41.85	21282	309.23	39.37	20228.67
	2	283.2	36.06	20664			
	3	315.8	40.21	18740			
LC(4-8mm)TC(8-16mm)	1	57.5	7.33	7369	55.27	7.04	8516.50
	2	55.1	7.011	6169.5			
	3	53.2	6.771	12011			
L1P(4-8mm)TC(8-16mm)	1	58.2	7.414	6880.8	55.30	7.04	6984.20
	2	53.3	6.787	6448.1			
	3	54.4	6.928	7623.7			
L5P(4-8mm)TC(8-16mm)	1	60.7	7.732	7625.7	62.10	7.91	7397.73
	2	62.2	7.92	7403			
	3	63.4	8.073	7164.5			
L1F(4-8mm)TC(8-16mm)	1	57.4	7.31	6893.3	53.03	6.75	6503.63
	2	47.6	6.056	6415.8			
	3	54.1	6.892	6201.8			

Table C.2. Splitting Tensile Strength (Pace Rate:0.94 kN/s).

Production Plan	Specimen Number	Max Load (kN)	Strength (MPa)	Average Values	
				Max Load (kN)	Strength (MPa)
CCSt(4-16mm)	1	151.60	4.83	147.87	4.71
	2	133.40	4.25		
	3	158.60	5.05		
CSt(4-8mm)TC(8-16mm)	1	51.40	1.64	52.60	1.67
	2	51.20	1.63		
	3	55.20	1.76		
LC(4-8mm)CSt(8-16mm)	1	122.50	3.90	138.17	4.42
	2	142.40	4.59		
	3	149.60	4.76		
LC(8-16)Cst(4-8)	1	136.30	4.34	125.57	4.00
	2	108.40	3.45		
	3	132.00	4.20		
LC(4-8 and 8-16)	1	87.80	2.79	89.87	2.86
	2	95.30	3.03		
	3	86.50	2.75		
L1P(4-8mm)CSt(8-16mm)	1	131.20	4.18	121.27	3.86
	2	102.70	3.27		
	3	129.90	4.14		
L1P(8-16)Cst(4-8)	1	133.90	4.26	102.30	3.26
	2	89.00	2.83		
	3	84.00	2.67		
L1P(4-8 and 8-16)	1	105.90	3.37	88.50	2.82
	2	74.30	2.36		
	3	85.30	2.72		
L5P(4-8mm)CSt(8-16mm)	1	124.30	3.96	121.73	3.88
	2	102.00	3.25		
	3	138.90	4.42		
L5P(8-16)Cst(4-8)	1	143.50	4.57	136.53	4.35
	2	134.30	4.27		
	3	131.80	4.20		
L5P(4-8 and 8-16)	1	95.90	3.05	90.03	2.87
	2	86.80	2.76		
	3	87.40	2.78		

Table C.2. Splitting Tensile Strength (Pace Rate:0.94 kN/s) (cont.).

Production Plan	Specimen Number	Max Load (kN)	Strength (MPa)	Average Values	
				Max Load (kN)	Strength (MPa)
L1F(4-8mm)CSt(8-16mm)	1	115.90	3.69	122.57	3.90
	2	111.00	3.53		
	3	140.80	4.48		
L1F(8-16)Cst(4-8)	1	140.70	4.48	133.30	4.24
	2	131.30	4.18		
	3	127.90	4.07		
L1F(4-8 and 8-16)	1	93.30	2.97	88.80	2.83
	2	98.60	3.14		
	3	74.50	2.37		
LC(4-8mm)TC(8-16mm)	1	44.10	1.40	40.60	1.29
	2	39.20	1.25		
	3	38.50	1.23		
L1P(4-8mm)TC(8-16mm)	1	45.30	1.44	40.50	1.29
	2	39.30	1.25		
	3	36.90	1.18		
L5P(4-8mm)TC(8-16mm)	1	43.50	1.38	43.70	1.39
	2	45.70	1.45		
	3	41.90	1.34		
L1F(4-8mm)TC(8-16mm)	1	37.70	1.20	36.53	1.16
	2	30.70	0.98		
	3	41.20	1.31		

Table C.3. Drop-Weight Impact Test (Blows to Failure).

Production Plan		Number of Blows		Average Values(x)		First Crack		Failure	
		Specimen Number	First Crack	Failure	Blows to First Crack	Blows to Failure	S.D. ( $\sigma$ )	Coefficient of Variation ( $\sigma/x$ )%	S.D. ( $\sigma$ )
CCSt(4-16mm)	1	415	416	481	482	105.5	21.92	105.5	21.87
	2	426	427						
	3	603	604						
CSt(4-8mm)TC(8-16mm)	1	320	470	307	423	81.3	26.48	86.65	20.49
	2	220	323						
	3	381	476						
LC(4-8mm)CSt(8-16mm)	1	303	304	312	313	84.33	27.06	84.33	26.97
	2	400	401						
	3	232	233						
LC(8-16)Cst(4-8)	1	277	278	340	341	104.8	30.83	104.8	30.74
	2	282	283						
	3	461	462						
LC(4-8 and 8-16)	1	69	70	85	86	14.18	16.68	14.18	16.49
	2	96	97						
	3	90	91						
L1P(4-8mm)CSt(8-16mm)	1	237	238	201	202	53.11	26.42	53.11	26.29
	2	140	141						
	3	226	227						
L1P(8-16)Cst(4-8)	1	145	146	211	212	58.79	27.88	58.79	27.69
	2	257	258						
	3	232	233						
L1P(4-8 and 8-16)	1	86	87	74	75	15.31	20.59	15.31	20.32
	2	57	58						
	3	80	81						
L5P(4-8mm)CSt(8-16mm)	1	172	173	134	135	35.84	26.81	35.84	26.61
	2	101	102						
	3	128	129						
L5P(8-16)Cst(4-8)	1	325	326	320	321	36.23	11.31	36.23	11.27
	2	354	355						
	3	282	283						
L5P(4-8 and 8-16)	1	97	98	117	118	18.33	15.67	18.33	15.53
	2	121	122						
	3	133	134						

Table C.3. Drop-Weight Impact Test (Blows to Failure) (cont.).

Production Plan	Specimen Number	Number of Blows		Average Values(x)		First Crack		Failure	
		First Crack	Failure	Blows to First Crack	Blows to Failure	S.D. ( $\sigma$ )	Coefficient of Variation ( $\sigma/x$ )%	S.D. ( $\sigma$ )	Coefficient of Variation ( $\sigma/x$ )%
L1F(4-8mm)CSt(8-16mm)	1	442	443	347	348	82.78	23.88	82.78	23.81
	2	293	294						
	3	305	306						
L1F(8-16)Cst(4-8)	1	334	335	378	379	43.03	11.38	43.03	11.35
	2	420	421						
	3	380	381						
L1F(4-8 and 8-16)	1	275	276	211	212	55.57	26.34	55.57	26.21
	2	175	176						
	3	183	184						
LC(4-8mm)TC(8-16mm)	1	185	395	227	361	40.20	17.68	36.82	10.19
	2	232	322						
	3	265	367						
L1P(4-8mm)TC(8-16mm)	1	87	115	116	210	29.01	25.08	90.01	42.86
	2	145	294						
	3	115	221						
L5P(4-8mm)TC(8-16mm)	1	93	281	125	245	43.09	34.47	72.09	29.42
	2	108	162						
	3	174	292						
L1F(4-8mm)TC(8-16mm)	1	149	171	114	151	41.48	36.49	34.36	22.80
	2	124	170						
	3	68	111						

Table C.4. Drop-Weight Impact Test ( Failure Impact Energy).

		Number of Blows				
Production Plan	Specimen Number	First Crack	Failure	First Crack Impact Energy (kN mm)	Failure Impact Energy (kN mm)	Average Failure Impact Energy(kN mm)
CCSt(4-16mm)	1	415	416	7901.185	7920.224	9183.144
	2	426	427	8110.614	8129.653	
	3	603	604	11480.52	11499.56	
CSt(4-8mm)TC(8-16mm)	1	320	470	6092.48	8948.33	8053.497
	2	220	323	4188.58	6149.597	
	3	381	476	7253.859	9062.564	
LC(4-8mm)CSt(8-16mm)	1	303	304	5768.817	5787.856	5952.861
	2	400	401	7615.6	7634.639	
	3	232	233	4417.048	4436.087	
LC(8-16)Cst(4-8)	1	277	278	5273.803	5292.842	6492.299
	2	282	283	5368.998	5388.037	
	3	461	462	8776.979	8796.018	
LC(4-8 and 8-16)	1	69	70	1313.691	1332.73	1637.354
	2	96	97	1827.744	1846.783	
	3	90	91	1713.51	1732.549	
L1P(4-8mm)CSt(8-16mm)	1	237	238	4512.243	4531.282	3845.878
	2	140	141	2665.46	2684.499	
	3	226	227	4302.814	4321.853	
L1P(8-16)Cst(4-8)	1	145	146	2760.655	2779.694	4042.614
	2	257	258	4893.023	4912.062	
	3	232	233	4417.048	4436.087	
L1P(4-8 and 8-16)	1	86	87	1637.354	1656.393	1434.271
	2	57	58	1085.223	1104.262	
	3	80	81	1523.12	1542.159	
L5P(4-8mm)CSt(8-16mm)	1	172	173	3274.708	3293.747	2563.919
	2	101	102	1922.939	1941.978	
	3	128	129	2436.992	2456.031	
L5P(8-16)Cst(4-8)	1	325	326	6187.675	6206.714	6117.865
	2	354	355	6739.806	6758.845	
	3	282	283	5368.998	5388.037	
L5P(4-8 and 8-16)	1	97	98	1846.783	1865.822	2246.602
	2	121	122	2303.719	2322.758	
	3	133	134	2532.187	2551.226	

Impact Energy per Blow, U= 19.039 kN mm

Table C.4. Drop-Weight Impact Test ( Failure Impact Energy) (cont.).

Production Plan	Specimen Number	Number of Blows		First Crack Impact Energy(kN mm)	Failure Impact Energy (kNmm)	Average Failure Impact Energy(kN mm)
		First Crack	Failure			
L1F(4-8mm)CSt(8-16mm)	1	442	443	8415.238	8434.277	6619.226
	2	293	294	5578.427	5597.466	
	3	305	306	5806.895	5825.934	
L1F(8-16)Cst(4-8)	1	334	335	6359.026	6378.065	7215.781
	2	420	421	7996.38	8015.419	
	3	380	381	7234.82	7253.859	
L1F(4-8 and 8-16)	1	275	276	5235.725	5254.764	4036.268
	2	175	176	3331.825	3350.864	
	3	183	184	3484.137	3503.176	
LC(4-8mm)TC(8-16mm)	1	185	395	3522.215	7520.405	6879.425
	2	232	322	4417.048	6130.558	
	3	265	367	5045.335	6987.313	
L1P(4-8mm)TC(8-16mm)	1	87	115	1656.393	2189.485	3998.19
	2	145	294	2760.655	5597.466	
	3	115	221	2189.485	4207.619	
L5P(4-8mm)TC(8-16mm)	1	93	281	1770.627	5349.959	4664.555
	2	108	162	2056.212	3084.318	
	3	174	292	3312.786	5559.388	
L1F(4-8mm)TC(8-16mm)	1	149	171	2836.811	3255.669	2868.543
	2	124	170	2360.836	3236.63	
	3	68	111	1294.652	2113.329	

Impact Energy per Blow,  $U = 19.039 \text{ kN mm}$

Table C.5. Pull Out Test.

Production Plan	Specimen Number	Ultimate Bond Strength(Mpa)	Bond Strength at 0.25mm Loaded End Slip(Mpa)	Bond Strength at 0.50mm Loaded End Slip(Mpa)	Bond Strength at 1.00mm Loaded End Slip(Mpa)	Average Values			
						Ultimate Bond Strength(Mpa)	Bond Strength at 0.25mm Loaded End Slip(Mpa)	Bond Strength at 0.50mm Loaded End Slip(Mpa)	Bond Strength at 1.00mm Loaded End Slip(Mpa)
CCSt(4-16mm)	1	8.91	0.8	1.82	4.29	11.44	0.60	1.66	5.06
	2	11.38	0.82	2.04	5.47				
	3	14.02	0.19	1.11	5.43				
CSt(4-8mm)TC(8-16mm)	1	6.23	1.1	2.26	5.31	5.08	1.51	2.84	4.70
	2	4.9	1.18	2.65	4.87				
	3	4.11	2.26	3.6	3.92				
LC(4-8mm)CSt(8-16mm)	1	12.78	1.57	3.35	7.18	12.15	1.36	3.16	7.08
	2	10.48	1.33	3.3	7.29				
	3	13.18	1.19	2.84	6.78				
LC(8-16)Cst(4-8)	1	11.88	0.13	1.05	1.41	9.50	0.42	1.41	3.05
	2	9.71	0.18	0.45	1.36				
	3	6.9	0.96	2.72	6.39				
LC(4-8 and 8-16)	1	7.91	0.93	3	6.76	8.52	0.83	2.57	6.05
	2	8.47	1.03	2.55	5.76				
	3	9.17	0.54	2.16	5.64				

Table C.5. Pull Out Test (cont.).

						Average Values			
Production Plan	Specimen Number	Ultimate Bond Strength(Mpa)	Bond Strength at 0.25mm Loaded End Slip(Mpa)	Bond Strength at 0.50mm Loaded End Slip(Mpa)	Bond Strength at 1.00mm Loaded End Slip(Mpa)	Ultimate Bond Strength(Mpa)	Bond Strength at 0.25mm Loaded End Slip(Mpa)	Bond Strength at 0.50mm Loaded End Slip(Mpa)	Bond Strength at 1.00mm Loaded End Slip(Mpa)
L1P(4-8mm)CSt(8-16mm)	1	10.61	0.25	1.85	5.46	8.62	0.66	1.96	4.86
	2	7.72	0.64	1.61	3.92				
	3	7.52	1.08	2.41	5.21				
L1P(8-16)Cst(4-8)	1	15.86	0.46	1.9	6.09	12.80	0.43	1.43	5.08
	2	9.95	0.51	1.62	5.46				
	3	12.59	0.32	0.77	3.7				
L1P(4-8 and 8-16)	1	6.77	0.57	1.72	4.63	10.30	1.12	2.66	6.12
	2	12.74	1.42	3.29	7.41				
	3	11.4	1.36	2.97	6.31				
L5P(4-8mm)CSt(8-16mm)	1	13.94	1.42	3.07	6.77	10.59	0.91	2.07	5.01
	2	13.5	1.18	2.84	6.53				
	3	4.34	0.12	0.3	1.73				
L5P(8-16)Cst(4-8)	1	13.06	0.21	1.43	5.11	14.74	0.53	1.97	6.10
	2	16.17	1.13	3	7.55				
	3	15	0.26	1.49	5.63				
L5P(4-8 and 8-16)	1	7.41	0.12	0.26	1.4	9.51	0.23	0.82	3.06
	2	11	0.24	0.99	3.49				
	3	10.13	0.34	1.22	4.29				

Table C.5. Pull Out Test (cont.).

						Average Values			
Production Plan	Specimen Number	Ultimate Bond Strength(Mpa)	Bond Strength at 0.25mm Loaded End Slip(Mpa)	Bond Strength at 0.50mm Loaded End Slip(Mpa)	Bond Strength at 1.00mm Loaded End Slip(Mpa)	Ultimate Bond Strength(Mpa)	Bond Strength at 0.25mm Loaded End Slip(Mpa)	Bond Strength at 0.50mm Loaded End Slip(Mpa)	Bond Strength at 1.00mm Loaded End Slip(Mpa)
L1F(4-8mm)CSt(8-16mm)	1	15.68	0.51	1.37	3.83	16.11	0.51	1.17	4.37
	2	15.45	0.23	0.64	3.27				
	3	17.19	0.8	1.5	6				
L1F(8-16)Cst(4-8)	1	11.32	0.92	2.5	6.52	14.33	0.57	1.98	5.74
	2	16.56	0.41	2.05	5.88				
	3	15.12	0.37	1.4	4.83				
L1F(4-8 and 8-16)	1	10.83	0.57	0.96	4.14	10.52	0.53	1.48	5.10
	2	11.38	0.54	1.75	5.75				
	3	9.34	0.49	1.72	5.41				
LC(4-8mm)TC(8-16mm)	1	7.76	0.11	0.45	3.16	6.54	0.27	0.97	3.60
	2	5.64	0.2	0.84	2.96				
	3	6.23	0.5	1.61	4.67				
L1P(4-8mm)TC(8-16mm)	1	4.98	0.73	1.79	4.17	5.64	0.53	1.32	3.41
	2	6.8	0.11	0.27	1.4				
	3	5.15	0.76	1.91	4.67				
L5P(4-8mm)TC(8-16mm)	1	4.57	0.31	0.74	2.28	5.23	0.32	1.03	3.43
	2	5.39	0.22	1.02	3.65				
	3	5.72	0.43	1.33	4.37				
L1F(4-8mm)TC(8-16mm)	1	5.79	0.11	0.32	2.2	4.57	0.15	0.47	2.33
	2	4.81	0.12	0.42	2.55				
	3	3.11	0.21	0.67	2.23				

Table C.6. Flexural Strength (Pace Rate: 0.02mm/s).

Production Plan	Specimen Number	Fracture Load(N)	Flexural Strength(MPa)	Average Values	
				Fracture Load(N)	Flexural Strength(MPa)
CCSt(4-16mm)	1	14027.51	9.47	13898.86	9.38
	2	13860.23	9.36		
	3	13808.85	9.32		
CCSt(4-8mm)TC(8-16mm)	1	6693.704	4.52	6398.60	4.32
	2	6156.336	4.16		
	3	6345.771	4.28		
LC(4-8mm)CSt(8-16mm)	1	12871.94	8.69	12924.86	8.72
	2	12811.82	8.65		
	3	13090.82	8.84		
LC(8-16)Cst(4-8)	1	11126.52	7.51	10796.66	7.29
	2	11178.2	7.55		
	3	10085.25	6.81		
LC(4-8 and 8-16)	1	6991.275	4.72	6951.32	4.69
	2	7674.057	5.18		
	3	6188.628	4.18		
L1P(4-8mm)CSt(8-16mm)	1	10396.74	7.02	11115.64	7.50
	2	11774.69	7.95		
	3	11175.5	7.54		
L1P(8-16)Cst(4-8)	1	9343.817	6.31	10166.28	6.86
	2	10398.61	7.02		
	3	10756.4	7.26		
L1P(4-8 and 8-16)	1	6843.119	4.62	7272.64	4.91
	2	7785.598	5.26		
	3	7189.205	4.85		
L5P(4-8mm)CSt(8-16mm)	1	9329.355	6.30	9516.16	6.42
	2	9128.741	6.16		
	3	10090.4	6.81		
L5P(8-16)Cst(4-8)	1	10419.39	7.03	10365.42	7.00
	2	10688.75	7.21		
	3	9988.119	6.74		
L5P(4-8 and 8-16)	1	7603.86	5.13	7174.34	4.84
	2	6236.408	4.21		
	3	7682.758	5.19		

Table C.6. Flexural Strength (Pace Rate: 0.02mm/s) (cont.).

Production Plan	Specimen Number	Fracture Load(N)	Flexural Strength(MPa)	Average Values	
				Fracture Load(N)	Flexural Strength(MPa)
L1F(4-8mm)CSt(8-16mm)	1	9933.038	6.70	9849.45	6.65
	2	9926.624	6.70		
	3	9688.684	6.54		
L1F(8-16)Cst(4-8)	1	11420.93	7.71	11824.35	7.98
	2	13014.08	8.78		
	3	11038.02	7.45		
L1F(4-8 and 8-16)	1	8530.008	5.76	9195.54	6.21
	2	9706.172	6.55		
	3	9350.45	6.31		
LC(4-8mm)TC(8-16mm)	1	4870.36	3.29	4849.63	3.27
	2	4793.623	3.24		
	3	4884.912	3.30		
L1P(4-8mm)TC(8-16mm)	1	4353.272	2.94	4686.51	3.16
	2	4817.251	3.25		
	3	4889.006	3.30		
L5P(4-8mm)TC(8-16mm)	1	5147.902	3.47	5055.42	3.41
	2	5015.413	3.39		
	3	5002.931	3.38		
L1F(4-8mm)TC(8-16mm)	1	4632.312	3.13	4523.06	3.05
	2	4411.28	2.98		
	3	4525.598	3.05		

Table C.7. Fracture Toughness (Pace Rate:0.02 mm/s).

Production Plan	Specimen Number	Fracture Toughness-1 (until the Ultimate-Max Load value ) (N mm)	Fracture Toughness-2 (until the last Load value of fracture) (N mm)	Average Values	
				Fracture Toughness-1 (until the Ultimate-Max Load value ) (N mm)	Fracture Toughness-2 (until the last Load value of fracture) (N mm)
CCSt(4-16mm)	1	3054.3	3742.2	2917.30	3616.23
	2	2897.4	3712.7		
	3	2800.2	3393.8		
CSt(4-8mm)TC(8-16mm)	1	1836.8	3044.4	1820.87	3055.80
	2	1599.1	2953.7		
	3	2026.7	3169.3		
LC(4-8mm)CSt(8-16mm)	1	2569.8	2985.8	2220.47	2700.83
	2	1895.2	2510.3		
	3	2196.4	2606.4		
LC(8-16)Cst(4-8)	1	1487.7	1892.1	1822.93	2095.57
	2	2034.7	2265.2		
	3	1946.4	2129.4		
LC(4-8 and 8-16)	1	1114.8	1289	1298.03	1461.63
	2	1629.3	1785.7		
	3	1150	1310.2		
L1P(4-8mm)CSt(8-16mm)	1	1383.8	1738.2	1835.97	2202.73
	2	1569.9	2007		
	3	2554.2	2863		
L1P(8-16)Cst(4-8)	1	2126.3	2263.3	1994.63	2180.73
	2	2242.7	2482.4		
	3	1614.9	1796.5		
L1P(4-8 and 8-16)	1	925.16	1101.4	929.85	1080.34
	2	1087.3	1242		
	3	777.08	897.62		
L5P(4-8mm)CSt(8-16mm)	1	1681.4	1841.4	1590.77	1895.53
	2	1366.4	1545.3		
	3	1724.5	2299.9		
L5P(8-16)CSt(4-8)	1	2144.7	2362.9	1699.10	1943.27
	2	1661.9	1794.6		
	3	1290.7	1672.3		
L5P(4-8 and 8-16)	1	1025.6	1130.9	928.66	1070.57
	2	856.04	1012.5		
	3	904.34	1068.3		

Table C.7. Fracture Toughness (Pace Rate: 0.02 mm/s) (cont.).

Production Plan	Specimen Number	Fracture Toughness-1 (until the Ultimate-Max Load value ) (N mm)	Fracture Toughness-2 (until the last Load value of fracture) (N mm)	Average Values	
				Fracture Toughness-1 (until the Ultimate-Max Load value ) (N mm)	Fracture Toughness-2 (until the last Load value of fracture) (N mm)
L1F(4-8mm)CSt(8-16mm)	1	1832.5	2332.3	1770.27	2195.97
	2	1813.5	2288.8		
	3	1664.8	1966.8		
L1F(8-16)Cst(4-8)	1	1861.4	2294.2	2020.17	2379.70
	2	2563	2697.8		
	3	1636.1	2147.1		
L1F(4-8 and 8-16)	1	1296.3	1436	1728.93	1947.97
	2	2466	2721.7		
	3	1424.5	1686.2		
LC(4-8mm)TC(8-16mm)	1	1088	2848	933.03	2401.63
	2	827.34	2207.3		
	3	883.76	2149.6		
L1P(4-8mm)TC(8-16mm)	1	588.88	1888.4	1170.99	3046.90
	2	1238.6	3617.3		
	3	1685.5	3635		
L5P(4-8mm)TC(8-16mm)	1	700.43	2136.4	795.93	1861.03
	2	822.22	1483.7		
	3	865.15	1963		
L1F(4-8mm)TC(8-16mm)	1	829.84	1504.7	838.30	1653.63
	2	818.47	1587.8		
	3	866.58	1868.4		

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