Journal of Advanced Civil Engineering Practice and Research
2550-1933 © Ababil Publishers
www.ababilpub.com/jacepr

Research Article

Mechanical properties and direct tensile strength of waste toner foamed concrete

N. M. Alkurdi*, F. A. Mohammad, H. A. Klalib

School of Architecture, Design and the Built Environment, Nottingham Trent University, 50 Shakespeare St, Nottingham, NG1 4FQ, UK
Corresponding author.Tel: 00447474200054; Email: nadir.alkurdi@ntu.ac.uk (Nadir M Alkurdi).

GRAPHICAL ABSTRACT

Foamed concrete production and testing

HIGHLIGHTS

- Cement content effect on the compressive strength of FC is examined.
- Effect of density and additives on FC mechanical properties is investigated.
- A direct tensile test to determine the tensile strength of FC is proposed.
- Direct tensile strength is compared with the indirect ones.
- Modulus of elasticity and stress-strain relationship of FC is obtained.

KEYWORDS

Foamed concrete (FC)
Compressive strength
Direct tensile strength
Stress-strain relationship
Waste toner
Sustainability

ARTICLE HISTORY

JACEPR-2020008
Received 14 November 2020
Received revision 17 December 2020
Accepted 27 December 2020
Available online 30 December 2020
Volume: 11, Issue: December 2020
(30 December 2020)

ABSTRACT

The use of Foamed Concrete (FC) in structural elements reduces dead loads on structures and foundations, contributes to cost reduction and energy-efficient construction by reduces the structural elements size, labour and energy during transportation and construction stages. To investigate the mechanical properties of FC including compressive, tensile and flexural strengths, modulus of elasticity and the stress-strain relationship, 256 specimens classified into four different densities (1200, 1400, 1600 and 1800 kg/m^3) were tested. For each concrete density, four mixes were designed including control mix and three different additives; silica fume, metakaolin and waste toner. The waste toner additive was collected from used printer cartridges. The experimental program was considered to introduce a modified direct tensile test, where splitting and flexural tests were conducted to confirm its reliability. The obtained results were quite converged, which illustrated that the tensile strength determined by the proposed model was lower than that of the Brazilian and flexural tests. The waste toner additive improved the FC compressive and tensile strengths by more than 30%. These results are promising and point to the significant potential of developing an eco-friendly lightweight concrete by replacement a percentage of cement with waste toner.

1. Introduction

The Foamed concrete (FC) is a new generation of lightweight concrete, it has lower compressive strength than normal-weight concrete, therefore, it was mostly used for non-structural applications such as road sub-bases, high volume void fills, reinstatement of utility trenches, soil stabilisation, grouting tunnel walls and trench reinstatement [1].

With the improvements in techniques and foaming agents, the use of FC has increased more rapidly than any other types of concrete product. FC has high strength- weight ratio, good workability and excellent thermal and soundproof performance [2]. Foamed concrete currently has been extensively used for floor screed and insulation, sub-base in highways, precast blocks, prefabricated insulation boards, precast wall elements/panels, and cast-in-situ / cast-in-place walls [3].

From sustainability and environmental point of view, FC is self-compacting concrete (SCC) Improves productivity and reduces power and noise as it does not require vibration during compaction and placement and reduce the power needed for handling and installation in case of precast concrete elements, resulting in an enormous saving in the overall cost [4]. Structurally, the use of FC reduces structural element size, less reinforcing steel and reduced concrete volume leads to a reduction of overall structure weight, which makes the structure behaves better under seismic loads [5].

Eurocode 2 [6] and American Concrete Institute [7] code do not cover FC design, but some research studies based on

ACI recommended empirical models and theories to predict the concrete mechanical properties including the tensile strength based on the compressive strength. It was recommended that a square root relationship between the cylinder compressive strength and the tensile strength. Another study has suggested that the power of compressive strength varies between 0.4 and 0.6 [8].

Raj et al. [9] stated that the splitting tensile strength of FC is around 10% of the cylinder compressive strength while the flexural strength is about 10-15%. Jones and McCarthy [10] reported that Young's modulus (E) of lightweight concrete is lower than that in normal-weight concrete. FC with a density between 300 – 1200 kg/m^3 has Young's modulus of 1 - 8MPa. In the ACI code, the strain at maximum stress of normal weight concrete is 0.003. Nevertheless, the strain at maximum stress for lightweight concrete exceeds 0.005 [11].

The tensile strength of concrete is often neglected when evaluating the ultimate load-bearing capacity of reinforced concrete elements [12]. However, it is still an important property of structural concrete members, it is significantly affecting the shear strength, deflection, development of crack patterns, and bond behaviour of structural elements [13]. Tensile strength is a key property of concrete, plays an important role in structural safety [14]. Several factors have been known to affect the tensile strength of concrete, such as the age of concrete, size of aggregate, the level of stress. Raj et al. [9], the splitting tensile strength of FC could be lower than those of normal weight concrete and lightweight aggregate concrete.

However, cement-sand based FC recorded a higher tensile strength than those with fly ash [15]. The high tensile strength of FC is mainly attributed to the bond capacity between sand particles and the cement paste [16]. The direct tensile strength of normal concrete is lower than the indirect tensile one, and the difference between them is about 25% [17].

The increase of concrete tensile strength is usually associated with an increase in the compressive strength. Nevertheless, concrete with higher strength is known to be more brittle, which represents a significant limitation for wide-range applications in innovative structural design [18]. The present study introduces a modified testing approach of a uniaxial direct tensile strength of FC to overcome conventional drawbacks associated with the indirect tensile tests. Also, it examines the effect of cement content, additives and density on the compressive strength, modulus of elasticity, and the direct and indirect tensile strength of FC.

The waste toner is a newly introduced material particular to Shawnim and Mohammad [19] and this research, hence, there are no wide published data available covers its application in structural lightweight concrete. The waste toner comes in the form of dry powder, collected from used printer cartridges, it is widely available as waste material for recycling and to help clean the environment by reducing buried waste and CO_2 emission [19].

2. Experimental programme

This experimental study involved 256 specimens classified into four groups of the following density variations; 1200, 1400, 1600 and 1800 kg/m^3, the density of the specimen range was chosen for foamed concrete based on the potential compressive strength showed in [19] study of reaching the required strength for structural applications (25MPa).

Accordingly, four different mixes (control, metakaolin, silica fume and waste toner) each group were designed to evaluate the additives effect on the mechanical properties of FC. Error! Reference source not found. shows the characteristics of foamed concrete mixes. There is no standard specification for FC mix design [20]. Therefore, to control the measured plastic density and the composition of the mix materials, the absolute volumes method was conducted in this study as it was approved working with FC in previous studies [19]. The method starts with a selection of target plastic concrete density, water/ binder (Cement + Additive) ratio and sand /cement ratio or the cement content [21]. Foamed concrete is typically designed for a target density to meet specific strength requirements [22].

The plastic density of FC mix can be determined from the weight of a sample in a container of known volume, the method is described in [23]. As stated by Hilal and Nicholas [24] in FC design it is allowed to have ± 50 kg/m^3 difference between target and measured plastic density. The dry density of foamed concrete can be calculated based on the following equation presented by [10].

$$\rho_{dry} = \frac{\rho_{Plastic} - 105}{1.05} \qquad \text{Eq. 1}$$

Where:

ρ_{dry} Measured dry density, and
$\rho_{plastic}$ Measured plastic density.

2.1 Specimen dimensions and specifications

Unlike normal weight concrete, FC is typically designed for a specific target density rather than a focus on the compressive strength only. The 256 specimens; cubes (100x100x100 mm), cylinders (150x300 mm) and prisms (100x100x500 mm) were cast, cured and tested according to British standards to determine the compressive, splitting tensile and flexural tensile strengths and modulus of elasticity. The modified direct tensile test was carried out on FC prism (100x100x500 mm), which were narrowed at the middle to control the failure location (
Fig. 1). Special steel claws made of bolts, nuts, and washers were designed, built and installed at both ends of the specimen as shown in (
Fig. 1).

The appropriate curing method for the specimens was the sealed curing, where the samples were wrapped in a cling film and stored at a constant temperature of 20^0C ± 2^0C for 28 days, this particular common curing regime was adopted by many researchers [3], [25] and [26].

Metakaolin (MK) is an ultra-fine cementitious pozzolanic material with a specific surface area ranging between 8000 – 12000 m^2/kg.

Table 1 Characteristics of concrete mixes with 1:1.5 C/S ratio.

Concrete mix reference	Target plastic density (kg/m^3)	Measured plastic density (kg/m^3)	Concrete mix proportions (kg/m^3)					Slump	*F_{cm} Cylinder
			Cement	Sand	Additive	Water	Foam (L/m^3)	(mm)	(MPa)
12CO	1200	1189	400	600	-	200	456	183	8.5
12MK	1200	1234	320	600	80	200	443	155	10.5
*12Ton	1200	1195	380	600	20	200	453	175	12.8
12SF	1200	1212	360	600	40	200	449	170	11
14CO	1400	1362	466.6	700.1	-	233.3	356	127	15.7
14Ton	1400	1373	443.3	700.1	23.3	233.3	353	120.5	20.6
*14MK	1400	1440	373.3	700.1	93.3	233.3	341	93	17.7
14SF	1400	1425	420	700.1	46.6	233.3	349	100	17.7
*16CO	1600	1569	533.3	800.5	-	266.6	257	108	28
16Ton	1600	1604	506.6	800.5	26.6	266.5	253	113	31
16MK	1600	1642	426.4	800.5	106.6	266.5	239	78	30.5
16SF	1600	1623	479.7	800.5	53.3	266.5	248	86.5	29.5
18CO	1800	1807	600	900	-	300	157	110	33.1
18Ton	`1800	1796	570	900	30	300	153	105	36.5
*18SF	1800	1841	540	900	60	300	147	87	34.2

***12Ton** is waste toner FC with a target plastic density of 1200kg/m^3.

***14MK** is Metakaolin FC with a target plastic density of 1400kg/m^3.

***16CO** is control (No additives) FC with a target plastic density of 1600kg/m^3.

***18FS** is silica fume FC with a target plastic density of 1800kg/m^3.

***F_{cm}** cylinder is the mean compressive strength of cylindrical concrete specimens after 28day.

Note: Only plastic density is presented in this study, the equation (1) can be used to convert it to dry density if needed.

2.2 Materials

The cement used was CEM I 42.5N, and the total cementitious material dosage used (cement, waste toner, metakaolin or silica fume) was between 350 and 600kg/m^3. The choice was based on previous research results which showed that is it not economical consuming more than 600kg/m^3 of cementitious material in foamed concrete also it showed only a slight strength improvement when increasing the cementitious material content above 650kg/m^3 [27].

The silica fume (SF) used is conforming to BS EN 13263-1 [28]. In order to improve the strength of FC, 10% of the total weight of the cement was replaced by SF. Error! Reference source not found. shows the chemical composition of the cement and the additives as a percentage by weight.

Fig. 1 Wooden framework and assembled gripping claw for the modified direct tensile test.

MK is an extremely active and effective pozzolanic material used in FC [29]. The mix is composed of 20% MK by the weight of the cement content. The percentages of additives (SF and MK) as replacement of cement by weight were chosen according to research conducted by [19] and [30].

Waste Toner (Ton) is a dry ink powder with the particle size of 5 – 20 µm, mainly made from a polyester resin/styrene acrylic copolymer which is brittle and has a low melting temperature of 110^0C. The waste toner used in this research is a mono-component type, it is magnetic and has a large proportion of binding resin and iron-oxides [31]. In FC mix, the waste toner replaced 5% of the cement by weight.

The natural siliceous sand used has a particle size of up to 4mm and conforming to BS EN 12620 [32], sieved to remove the particles greater than 2.36 mm in diameter [25], which leads to improving the stability and flowability of the fresh concrete. The coarse aggregate was not used in the FC mix as the fine air void structures would not stand its relatively heavyweight, which may lead to segregation. The mixing of water for the FC complied with BS EN1008 [33].

The protein surfactant is a chemical admixture which was incorporated into the mix to produce the formation of stable air bubbles (foam). Furthermore, some researchers found that the protein surfactant increases the foam strength/density ratio by 50 to 100% in comparison to a synthetic surfactant [34].

Therefore, the commercially available protein surfactant, known as ProPump-Protein 40, was used to produce the pre-formed foam aiming to achieve a low-density and long-lasting air bubbles structure. The solution's concentration of the used surfactant was 50 g per litre of water to produce the aimed foam density of 50 ± 5 kg/m^3.

2.3 Test methods

Producing foam with a density of 50 ± 5 kg/m^3 required 50g of surfactant in a litre of tap water to prepare the aqueous surfactant solution. Foam is produced by a foam generator as shown in Error! Reference source not found.**A.** As no standard controls foamed concrete production, the procedure described by Gangatire and Suryawanshi [20], and followed by most researchers is applied in this study for the FC production as shown in Error! Reference source not found.**D.**

The dry constituents (cement, fine aggregate and additives) were combined in the ordinary mixer with a speed of 1.57 rad/s, for about a minute followed by water to be mixed properly for about 2-4 minutes or up until a homogeneous mix with no lumps is obtained. In the meantime, the pre-formed foam is produced by foam generator, to be added to the base mix immediately. The mix then is combined until the foam is evenly distributed throughout the mix.

The initial selection of cementitious material /sand ratios (C/S) to determine the effect of the cement content on FC compressive strength were 1:2, 1:1.5 and 1:1. However, based on the results from the initial testing, the ratio (C/S) of 1:1.5 was chosen for the rest of the experiment.

To examine the indirect tensile strength of FC, two tests were performed; the splitting tensile test according to BS EN 12390-6 [35] and the four-point flexural test according to BS EN 12390-5 [36]. The compressive strength, modulus of elasticity and stress-strain behaviour were examined using cylinder test specimens conforming to BS EN 12390-3 [37] as**Error! Reference source not found.**.

The specimens were classified into four different groups based on plastic densities (1200, 1400, 1600 and 1800kg/m^3), and four FC mixes were used for each group (control, silica

Table 0 Chemical composition and main properties of cement and additives by weight.

Compounds/ properties	CEM I 42.5N	Silica fume	Metakaolin	Waste toner
CaO	64.45	1.9	0.01	2.5
SiO_2	22.25	96.95	56.7	10-14
Binder Resin	-	-	-	60-85
Al_2O_3	4.75	0.25	39.8	-
Fe_2O_3	3.35	0.15	0.51	10-20
Carbon black- C	-	-	-	0.1-5
SO_3	1.95	0.00	0.00	0.05
Ground sand	-	-	-	1-5
MgO	1.45	0.25	0.25	-
K_2O	0.9	0.15	1.82	-
TiO_2	0.35	0.35	0.81	0.01
Na_2O	0.35	-	0.09	-
MnO	0.20	-	0.01	-
Density (g/cm^3)	3.15	2.25	2.60	1.7
Particle size distribution				
D90 (µm)	34.24	7.35	8.07	-
D50 (µm)	12.38	1.73	1.90	31.5
D10 (µm)	1.64	1.85	0.69	68.5

fume, metakaolin, and waste toner). All specimens were cured for 28 days according to BS EN 12390-2 [38].

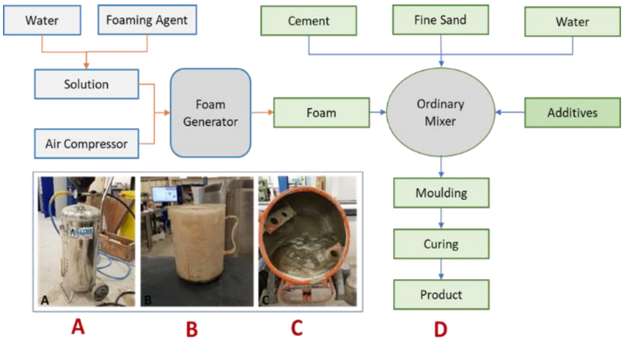

Fig. 2 Foam production and use in FC showing (A) Foam generator (B) Foam (C) Foam mixed with raw concrete (D) FC production using a pre-foamed method.

It should be noted that several test methods have attempted to determine the tensile strength in concrete and reflect real-world settings [39]. Therefore, a direct tensile strength test under uniaxial tensile was developed and carried out using the specimen as shown in Error! Reference source not found.. Studies conducted by Alhussainy et al. [12] and Swaddiwudhipong et al. [40] adopted similar techniques to determine the direct tensile strength for normal weight concrete and lightweight aggregate concrete. However, the developed method in the current study is more practical, simple and proved sufficiently accurate measurements.

Fig. 3 FC testing for (A) Compressive strength, (B) Flexural strength and (C) Splitting tensile strength.

A hydraulic testing machine with a maximum load of 30 kN was used to apply a uniaxial direct tensile load on the specimen as shown in **Fig. 4**. The tensile load were applied gradually, with a rate of 100 N/sec. Two tensile grips were attached to the chains part of the specimens to facilitate the uniaxial perfectly-aligned loading. Two strain gauges were placed in transverse and longitudinal directions to measure the deformation of the specimen during loading. All the samples were tested at 28 days.

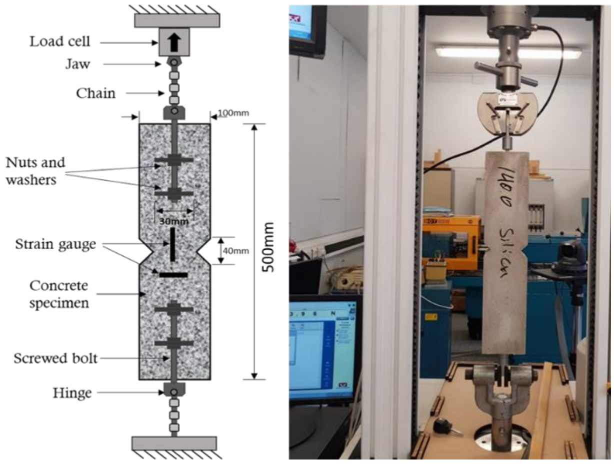

Fig. 4 Set-up for direct tensile testing.

The direct tensile splitting strength f_t is given by Eq.2:

$$f_t = \frac{F}{b.d} \qquad \text{Eq. 2}$$

Where:

f_t	Direct tensile strength
F	Measured peak load
d	Depth of specimen
b	Width of the specimen, the whole width

3. Results and discussions

This section presents the effect of cement content, density and additives on FC mechanical properties also cover the direct and indirect tensile strengths.

3.1 Effect of cement content

It is clear that the samples with higher cementitious material content have higher compressive strength as shown in Error! Reference source not found.. For instance, mixes of 1:1.5 *C/S* ratio displayed an average of 26.2% higher compressive strength than mixes of 1:2 ratio. However, the compressive strength of specimens of 1:1 ratio has shown an average increase of less than 4% compared to mixes of 1:1.5 ratio.

Consequently, the cement content has a minor effect on the compressive strength when the c/s ratio is greater than 1:1.5. Which indicates that FC with higher binder content (but not more than 650 kg/m^3) has greater bonding properties, which subsequently increases its compressive strength. However, when the binder content exceeds 650 kg/m^3 the compressive strength improvement is insignificant. For that reason, it is clear that the relationship between compressive strength and binder content is a direct nonlinear relationship.

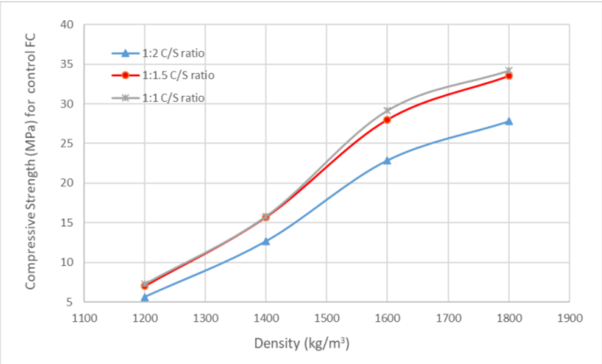

Fig. 5 Effect of cement content on FC compressive strength.

3.2 Effect of density

It was found that the FC compressive strength is directly proportional to its density. The higher the density, the greater the compressive strength. The increase of FC density from 1200 to 1800kg/m^3, rises the compressive strength by an average of 350%. The pore structure of foamed concrete plays a dominant role in controlling its compressive strength, which means a denser concrete generally provides higher compressive strength as shown in Error! Reference source not found..

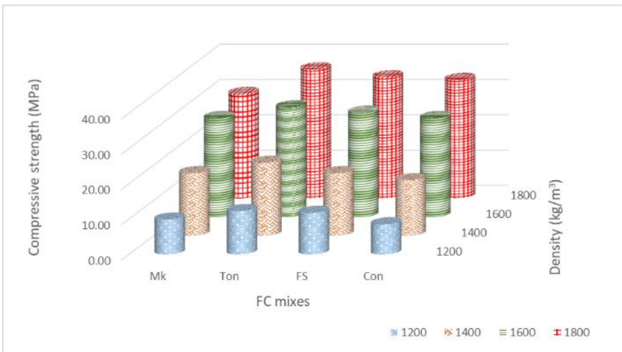

Fig. 6 The effect of FC density on compressive strength.

When the foamed concrete has a compressive strength of 8MPa or less, the direct tensile, splitting and flexural strengths have almost the same value according to **Fig. 7**. However, the splitting tensile strength is higher than both flexural and direct tensile strengths when the compressive strength greater than 8MPa. The average of flexural tensile strength is found to be only 3% higher than the average of the direct tensile strength. However, for all FC specimens, the average splitting tensile strength is 18% higher than the average of direct tensile strength.

Based on the results of the relatively large number of specimens tested for all densities (1200-1800 kg/m^3) for waste toner FC, the relationships between tensile strengths with regards to the compressive strength are as follow:

$$f_r = 0.38\,(f'c)^{0.65} \qquad \text{Eq. 3}$$

$$f_{sp} = 0.26\,(f'c)^{0.83} \qquad \text{Eq. 4}$$

$$f_t = 0.47\,(f'c)^{0.57} \qquad \text{Eq. 5}$$

Where:

f_r Flexural tensile strength, MPa
f_{sp} Splitting tensile strength, MPa
f_t Direct tensile strength, MPa
$f'c$ Compressive strength, MPa

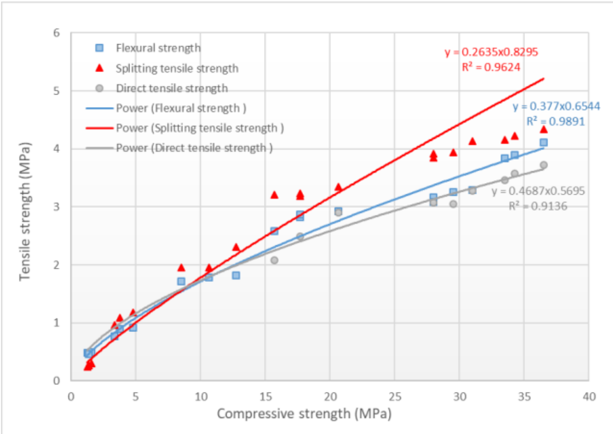

Fig. 7 Tensile strengths from direct and indirect tension tests.

The bond between high FC density components is higher than in a lower concrete density, which means the higher the density, the greater the direct tensile strength as shown in **Fig. 8**. For instance, by increasing the FC density from 1400 to 1800kg/m^3, the direct tensile strength rose by more than 65%.

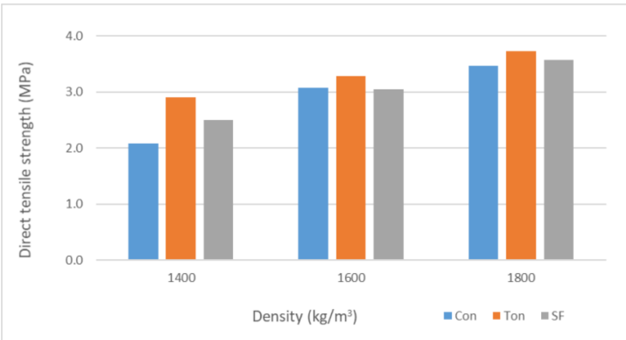

Fig. 8 Effect of FC density and additives on the direct tensile strength.

Several studies [41], [17] and [12], agreed that in concrete the direct tensile strength is lower than the indirect tensile strength. Which can be explained by the fact that during the direct tensile test, the failure surface has less resistance to the applied force as it is perpendicular to the direction of applied force. However, in the indirect tensile test such as the Brazilian test, the cylindrical sample is subjected to diametrical compression stresses as shown in Error! Reference source not found.**9**. These stresses applied over a small width throughout the sample's length and with a controlled load area to avoid the concentration of stresses and compensate small irregularities on the surface of the sample [42].

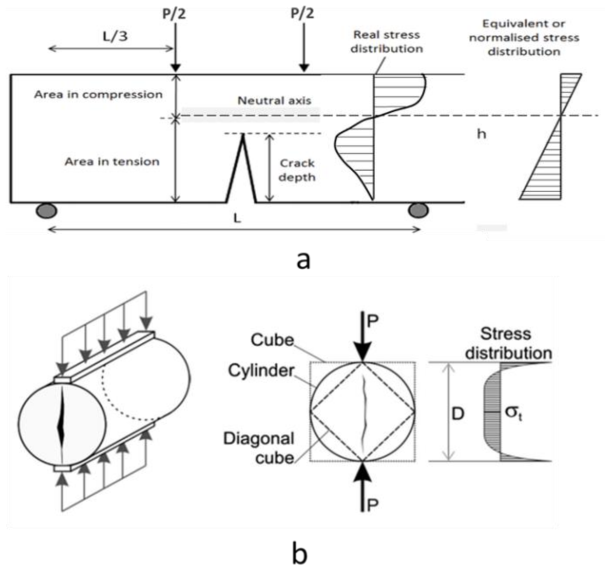

Fig. 9 Loading and expected failure mode of concrete indirect tensile tests: (a) Four-point flexural teste, (b) Brazilian splitting test.

The FC modulus of elasticity is found to be directly proportional to the density. It means that the higher the density, the greater the modulus of elasticity. The average improvement of modulus of elasticity increased by 330% when the density increased from 1200 to 1800kg/m^3 as illustrated in **Fig. 10**.

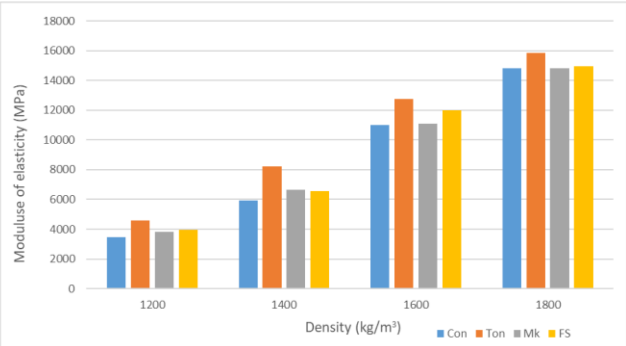

Fig. 10 Effect of FC density and additives on the modulus of elasticity.

The stress-strain relationships of normal and waste toner foamed concrete obtained from the static modulus of elasticity test are presented in **Fig. 11**. It was observed that FC has greater strain at maximum stress than normal-weight concrete, which means FC is more flexible material than normal concrete. However, the increase of FC compressive strength decreases its flexibility and become more brittle material, where foamed concrete with a density of 1800 kg/m^3 or more has a stress-strain relationship close to normal weight concrete.

Modulus of elasticity was determined from the slope of the stress-strain compression and direct tension curves. **Fig. 12** demonstrates the modulus of elasticity (E) obtained from the dynamic modulus of elasticity test for waste toner FC with compressive strength less than 27 MPa is found to be higher than the one obtained from a direct tensile test. Though, the values of (E) obtained from the direct tensile test are greater than the ones obtained from the compression test when the compressive strength higher than 27 MPa.

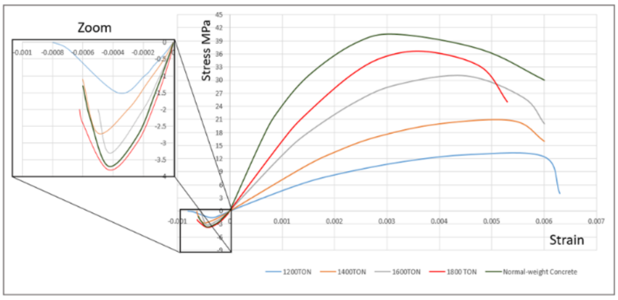

Fig. 11 FC stress-strain relationship of normal weight and foamed concrete.

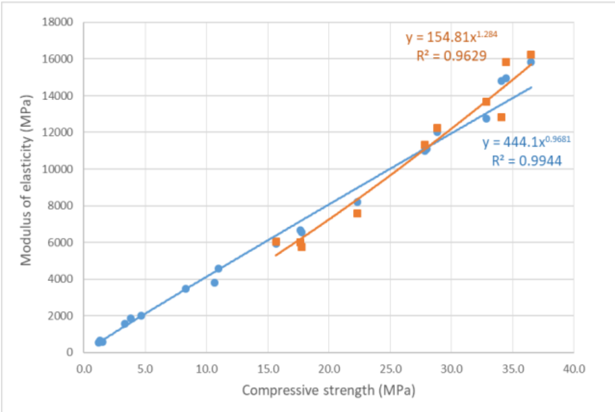

Fig. 12 Modulus of elasticity from compression and tensile tests.

3.3 Effect of additives

The use of additives (MK, SF and Ton) in FC improved the compressive strength of the concrete. The FC compressive strength increased by 18.2% when MK replaced 20% of cement content. However, the metakaolin in FC mixes seems to initiate a kind of chemical reaction (pozzolan reaction) which affected the stability of the air bubbles structure, and this process increases the density of the concrete density ending up with higher measured plastic density than the target plastic density by 8%.

Moreover, the use of MK in FC mixes generated an increase of heat due to an increase in hydration. Therefore, after 24 hours, the specimens were about 6 - 8^{o}C higher in temperature than those of other mixes. It was found that silica fume (SF) increases the FC compressive strength by an average of 10%. However, the waste toner additive has a higher impact on the compressive strength of FC, which increased by an average of 30% as shown in **Fig. 13**.

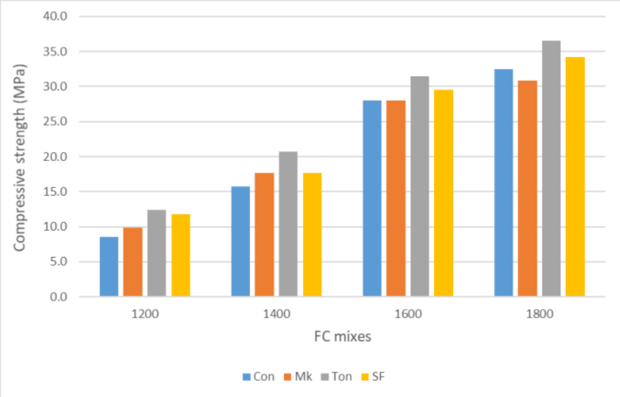

Fig. 13 FC compressive strength for all mixes.

The use of additives improves the flexural, splitting and direct tensile strengths of FC. The tensile strength increased by an average of 6% with MK and by 5% with SF. However, waste toner had a higher impact on all tensile strengths, which could be associated with the high proportion of binder Resin that waste toner contains. Where the tensile strengths of waste toner foamed concrete increased by about 11% compared with the control ones. **Fig. 14** illustrates the direct tensile strength is lower than both splitting and flexural tensile strengths. Moreover, it is clear that splitting tensile is higher than flexural and direct tensile strength in all FC mixes.

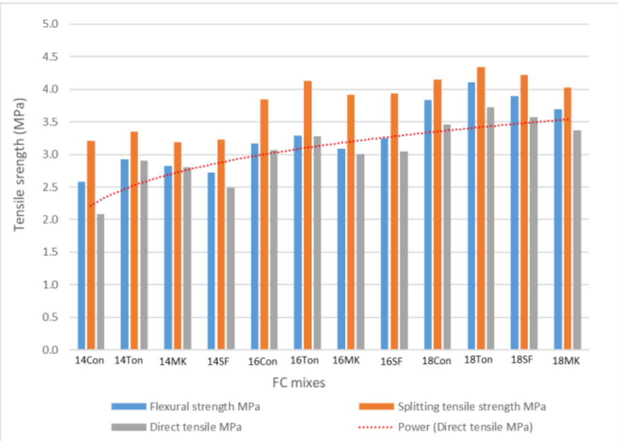

Fig. 14 Effect of FC density and additives on tensile strength.

4. Discussion of results

The results obtained in this study are evaluated by comparing them with previous comparable studies results. Compressive strength to density ratio is a feature in FC hence, it was compared to other types of concrete. As shown in **Fig. 15**, FC (18 Ton) compressive strength to density ratio conforms with FC in the study by Falade et al. [41]. However, the ratio is reasonably higher than the one found by Ramamuth and Nambiar [27], Hilal [24], and Jones and McCathy [43]. It was noticed that waste toner FC has higher compressive strength to density ratio than lightweight aggregate concrete (LWAC), which highlight the potential use of waste toner FC in structural applications.

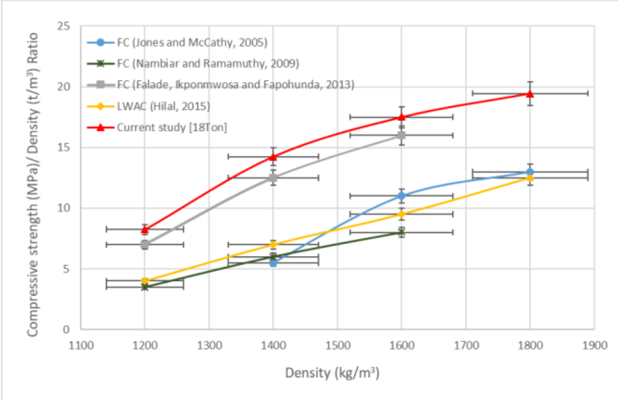

Fig. 15 Concrete compressive strength/ Density ratio of different studies.

Fig. 16 represents the splitting tensile strength versus the compressive strength for LWC, LWAC and FC with densities ranging from 800-1800 kg/m^3. It can be seen that waste toner FC in the current study has higher splitting tensile strength than the cited studies of Babu [44], Jones and McCarthy [43] with lightweight aggregate and foamed concrete, which might result from a great adhesion between the small sand particles with the cement paste according to Ghorbani et al. [45].

Furthermore, the splitting tensile strength of FC in [41] strongly conforms with the results of waste toner FC obtained in this study. Falade et al. [41] used Pulverized Bone as an additive to FC, which contains around 10% of silicon dioxide (SiO2) which almost the same amount that waste toner does. Zhuang and Chen [46] cited that silicon dioxide improves the mechanical properties of concrete including bending and tensile strength.

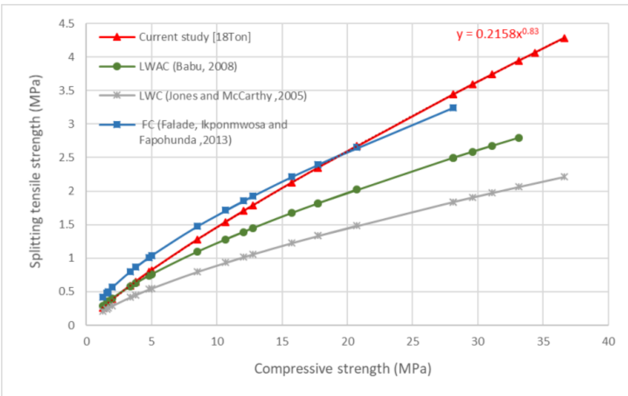

Fig. 16 Relationship between splitting tensile strength and compressive strength of LWC, LWAC and FC.

The relationships of concrete compressive strength and splitting tensile strength are shown in **Fig. 16** and represented by the following equations in **Table 3**.

According to **Fig. 17**, foamed concrete with waste toner has a lower modulus of elasticity than both NWC in Neville [47] study and FC in the study of Jones et al. [48].

Table 3 The relationships of concrete compressive strength and splitting tensile strength.

Author	Equation	
The current study for waste toner FC	$f_{sp} = 0.22\,(f'c)^{0.83}$	*Eq. 6*
Babu (2008) for LWAC	$f_{sp} = 0.28\,(f'c)^{\,0.69}$	*Eq. 7*
Jones and McCarthy (2005) for LWC	$f_{sp} = 0.2\,(f'c)^{0.7}$	*Eq. 8*
Falade et al., (2013) for FC	$f_{sp} = 0.4\,(f'c)^{0.66}$	*Eq. 9*

Where:

f_{sp} The splitting tensile strength, MPa

$f'c$ The compressive strength, MPa

However, waste toner FC modulus of elasticity seems to be similar to that of the prediction in BS 8110 BS [49] for LWC and Jones and McCarthy [10] for FC with coarse Fly Ash.

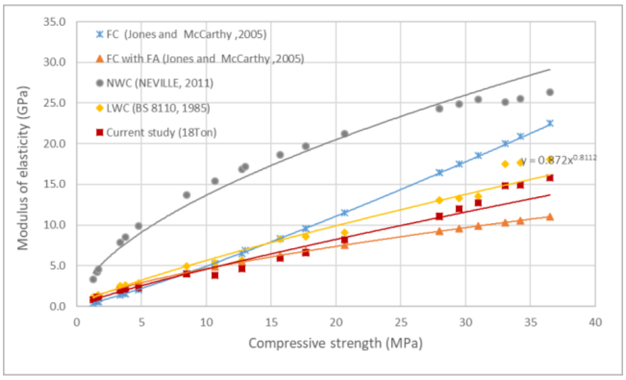

Fig. 17 Relationship between compressive strength and modulus of elasticity of NWC, LWAC, LWC and FC.

Table 4 The relationships of concrete compressive strength and modulus of elasticity.

Author	Equation	
The current study waste toner FC	$E = 0.41\,(f'c)^{0.99}$	*Eq. 10*
Jones and McCarthy (2005) for FC with coarse FA	$E = 0.99\,(f'c)^{0.67}$	*Eq. 11*
Neville (2011) for NWC	$E = 11.71(f'c)^{0.33} - 8.3$	*Eq. 12*
(Jones and McCarthy, 2005) for FC	$E = 0.42\,(f'c)^{1.18}$	*Eq. 13*
(BS 8110, 1985) for LWC	$E = 0.872\,(f'c)^{0.81}$	*Eq. 14*

Where:

E The modulus of elasticity, MPa

$f'c$ The compressive strength, MPa

In addition, according to Shawnim and Mohammad [19], the reactions between the constituents of waste toner with the chemical composition of the binding material produce a strong bond between the fine aggregate and the cement matrix. As a result, the compressive strength and modulus of elasticity obtained are relatively high in waste toner FC than normal FC. However, the waste toner FC still has a lower modulus of elasticity than those achieved by NWC.

Leading to a conclusion that a direct substitution of FC for the same compressive strength grade of NWC might not give a similar structural performance. The modulus of elasticity of waste toner foamed concrete can according to this study derived by means of Eq. 10.

The relationships between the compressive strength and modulus of elasticity for waste toner FC are shown in **Fig. 17** and represented by the following equations in **Table 4**.

5. Conclusions

The present study examined the mechanical properties of foamed concrete and investigate the effect of cement content, density and additives especially waste toner on the compressive strength, modulus of elasticity, and the direct and indirect tensile strength of FC. An experimental campaign was conducted using 256 FC samples. Compression, splitting tensile, flexural and a developed uniaxial direct tensile tests were carried out. The obtained results were compared with other available data from the literature, and the findings are summarised below:

- Cementitious material/sand ratio is directly proportional to the FC compressive strength. However, when the cement content is over 650kg/m^3, the compressive strength showed only a slight improvement. The mechanical properties FC are directly proportional to its density.
- Waste toner as an additive has the highest effect on FC mechanical properties than MK and SF. It increases compressive strength by an average of 30%.
- The tensile strength of FC obtained from the direct tensile testing is lower than that of flexural and splitting tests.
- The proposed empirical equation determining the splitting tensile strength of waste toner FC conforms with that developed in the study by Falade et al., [41] for FC.
- The modulus of elasticity of waste toner FC is found to be lower than that in NWC, SSC and LWAC. However, the proposed empirical equation determining the modulus of elasticity of the FC aligns with that in Jones et al., [43] study for FC.
- Waste toner foamed concrete with a plastic density ranging between 1400-1800kg/m^3, is an eco-friendly material, which has a great potential to be used in structural applications. It is recommended that another study investigates the structural behaviour of waste toner FC, with lightweight reinforcement such as Glass Fibre Reinforced Polymer (GFRP) rebar.

List of Abbreviations

ACI	American Concrete Institute
C	Cement
FA	Fly Ash
FC	Foamed concrete
LWAC	Lightweight aggregate concrete

LWC Lightweight concrete
MK Metakaolin
S Sand
SCC Self-compacting concrete
SF Silica fume
Ton Waste toner
W Water

List of Notations

b Width of the specimen (mm)
d Depth of specimen (mm)
E Modulus of Elasticity (MPa)
F Measured peak load (KN)
F_{cm} The mean compressive strength of cylindrical concrete specimens after 28day (MPa)
$f'c$ Compressive strength of concrete (MPa)
f_t Direct tensile strength of concrete (MPa)
f_r Flexural tensile strength of concrete (MPa)
f_{sp} Splitting tensile strength of concrete (MPa)

Acknowledgements

The Libyan Ministry of Higher Education and Sabratha University-Libya funded the PhD research of the author. The authors wish to thank participants for completing the experiments, who directly or indirectly contributed to this research.

References

[1] Falliano D, Domenico D De, Ricciardi G, Gugliandolo E. 3D-printable lightweight foamed concrete and comparison with classical foamed concrete in terms of fresh state properties and mechanical strength. Constr Build Mater. 2020;254:119271.
[2] Zhang Y, Chen D, Qu K, Lu K, Chen S, Kong M. Study on engineering properties of foam concrete containing waste seashell. Constr Build Mater. 2020;260:119896.
[3] Jalal M, Tanveer A, Jagdeesh K, Ahmed. F. Foam Concrete. 2017;8.
[4] Ozlutas K. Behaviour of ultra - Low density foamed concrete. 2015;1.
[5] Jones MR, Ozlutas K, Ouzounidou A, Rathbone RF. Behaviour of PC / CSA / FA Blends in Foamed Concrete. 2013;4.
[6] BS EN 1992-1. Design of concrete structures-Part 1,: General rules and rules for buildings, 1992-1-1.
[7] ACI 318-05. Building code requirements for structural concrete and commentary (ACI 318R-05) report. 2004.
[8] Hilal AA. Properties and Microstructure of Pre-formed Foamed Concretes Properties and Microstructure of Pre-formed Foamed Concretes. PhD thesis, University of Nottingham, UK, 2015.
[9] Amritha Raj, Dhanya Sathyan KMM. Physical and functional characteristics of foam concrete: A review. Constr Build Mater. 2019;221:787–99.
[10] Jones MR, McCarthy A. Preliminary views on the potential of foamed concrete as a structural material. Mag Concr Res. 2005;57(1):21–31.
[11] Barton SG, Bell LW, Berg GRU, Cook JE, Cook R, Costa WJ. Standard Practice for Selecting Proportions for Structural Lightweight Concrete (ACI 211.2-98) 1998;98:1–18.
[12] Alhussainy F, Hasan HA, Rogic S, Neaz Sheikh M, Hadi MNS. Direct tensile testing of Self-Compacting Concrete. Constr Build Mater. 2016;112:903–6.
[13] Trevor, GA. Investigating a reinforced lightweight foamed concrete walling system for low-rise residential buildings in moderate seismic regions. J Build Eng. 2018;20:663–70.
[14] van Rooyen AS. Structural lightweight aerated concrete. 2013:102.
[15] Saidani M, Ogbologugo U, Coakley E, George S. Lightweight cementetious (GEM-TECH) structural material. Proc Int Congr Technol Concr Durab. 2016;186–95.
[16] Al-Shannag MJ, Charif A. Bond behavior of steel bars embedded in concretes made with natural lightweight aggregates. J King Saud Univ - Eng Sci. 2017;29(4):365–72.
[17] Choi S-J, Yang K-H, Sim J-I, Choi B-J. Direct tensile strength of lightweight concrete with different specimen depths and aggregate sizes. Constr Build Mater. 2014;63:132–41.
[18] De Villiers J. Bond behaviour of deformed steel in lightweight foamed concrete. 2015.
[19] Shawnim PA, Mohammad F. Toner Used in the Development of Foamed Concrete for structural use. 2018;9(1):27–33.
[20] Gangatire OS, Suryawanshi YR. Structural Behaviour of Lightweight concrete with Conventional Concrete. 2016;6(2):635–8.
[21] Gupta S. Materials Today : Proceedings Development of a strength model for foam concrete based on water – cement ratio. Mater Today Proc. 2020;1571.
[22] Hulusi O, Gholampour A, Gencel O, Ozbakkaloglu T. Physical and mechanical properties of foam concretes containing granulated blast furnace slag as fine aggregate. Constr Build Mater. 2020;238:117774.
[23] BS EN 12350-6. Testing fresh concrete - Part 6: Density. 2009.
[24] Hilal A, Nicholas H, Andrew R. The Use of Additives to Enhance Properties of Pre- Formed Foamed Concrete. Int J Eng Technol. 2015;7(4).
[25] Ikponmwosa E, Falade F, Fapohunda C, Akinniyi T, Olori K. Effect of Foam Concentration on Structural Characteristics of Steel Reinforced Aerated Concrete Beams. Pacific J Sci Technol. 2014;15(1):32–46.
[26] Kearsley EP, Wainwright PJ. The effect of high fly ash content on the compressive strength of foamed concrete. Cem Concr Res. 2001;31(1):105–12.
[27] Ramamurthy K, Nambiar K. A classification of studies on properties of foam concrete. Cem Concr Compos. 2009;31(6):388–96.

[28] BS EN 13263-1. Silica fume for concrete - Part 1: Definitions, requirements and conformity criteria. 2009;3.
[29] Mohammad M. Development of foamed concrete: enabling and supporting design. PhD thesis, University of Dundee, UK, 2011.
[30] Koksal F, Sahin Y, Gencel O. Influence of expanded vermiculite powder and silica fume on properties of foam concretes. Constr Build Mater. 2020;257:119547.
[31] Pirela S V., Sotiriou GA, Bello D, Shafer M, Bunker KL, Castranova V et al. Consumer exposures to laser printer-emitted engineered nanoparticles: A case study of life-cycle implications from nano-enabled products. Nanotoxicology 2015;9(6):760–8.
[32] BS EN 12620. Aggregates for concrete. 2009.
[33] BS:EN:1008:2002. Mixing water for concrete. Specification for sampling, testing and assessing the suitability of water, including water recovered from processes in the concrete industry, as mixing water for concrete. BSI Stand. 2002;3.
[34] Markin V, Nerella VN, Schröfl C, Guseynova G, Mechtcherine V. Material design and performance evaluation of foam concrete for digital fabrication. Materials (Basel) 2019;12(15).
[35] BS EN 12390-6. Testing hardened concrete- Part 6: Tensile splitting strength of test specimens. Aberdeen's Concr Constr. 2009;38(10).
[36] BS EN 12390-5. Testing hardened concrete- part 5: Flexural Strength Test. Constr Stand. 2009;2(2):1–14.
[37] BS EN 12390-3. Testing hardened concrete- Part 3: Compressive strength of test specimens. 2009.
[38] BS EN 12390-2. Testing hardened concrete- Part 2: Making and curing specimens for strength tests. 2000.
[39] Resan SF, Chassib SM, Zemam SK, Madhi MJ. New approach of concrete tensile strength test. Case Stud Constr Mater. 2020;12:1–13.
[40] Swaddiwudhipong S, Lu HR, Wee TH. Direct tension test and tensile strain capacity of concrete at early age. Cem Concr Res. 2003;33(12):2077–84.
[41] Falade F, Ikponmwosa E, Fapohunda C. A Study on the Compressive and Tensile Strength of Foamed Concrete Containing Pulverized Bone as a Partial Replacement of Cement. J Engg Appl Sci. 2013;13:82–93.
[42] Slag Cement Association S. Compressive and Flexural Strenght. Concrete. 2013;91(14):489–93.
[43] 43. Jones R, Mccarthy A, Kharidu S, Nicol L. Foamed concrete developments and applications. Concr. 2005;39(8):41–3.
[44] Babu DS. Mechanical and deformational properties, and shrinkage cracking behaviour of lightweight concretes. Natl Univ Singapore 2008;49:69–73.
[45] Ghorbani S, Sharifi S, de Brito J, Ghorbani S, Jalayer MA, Tavakkolizadeh M. Using statistical analysis and laboratory testing to evaluate the effect of magnetized water on the stability of foaming agents and foam concrete. Constr Build Mater. 2019;207:28–40.
[46] Zhuang C, Chen Y. The effect of nano-SiO_2 on concrete properties: A review. Nanotechnol Rev. 2019;8(1):562–72.
[47] Neville A. Properties of Concrete, 4th. London: Pitman Publishing. 2011.
[48] Jones R, Mccarthy A, Kharidu S, Nicol L. Foamed concrete developments and applications. Concr. 2005;39(8):41–3.
[49] BS 8110-1: Structural Use of Concrete. Vol. 5, BS 8110. 1985.

To cite this article: Alkurdi NM, Mohammad FA, Klalib HA. Mechanical properties and direct tensile strength of waste toner foamed concrete. Journal of Advanced Civil Engineering Practice and Research 2020;11:10-20.

To link this article: http://ababilpub.com/download/jacepr11-3/