

## Mechanical Performance of Reinforced Concrete with Different Proportions and lengths of Basalt Fibres

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### Abstract

This paper discusses the effect of the fraction (0.2-0.3% by volume) and length (22 mm and 24 mm) of basalt fibre on the mechanical properties of concrete. The paper aims to evaluate the effect of different combinations of basalt fibres on the mechanical properties of concrete, as well as identify the best basalt fibre length and content that have the optimum influence on concrete. This paper is considered to be distinct from other research work as it fills the literature gap by presenting new unknown facts and also adds new knowledge. For example, it identifies the best basalt fibre length and content combination that demonstrates an improvement in the mechanical properties of concrete. It suggests the use of a blend of 12 mm short and 24 mm long fibres as they have a significant effect on the mechanical properties of concrete, it validates the results obtained from the laboratory by using a statistical analysis of variance ANOVA software, as well as determine the correlation between the mechanical properties of concrete. The results showed that the optimum basalt fibre length and content that enhanced the mechanical properties of concrete is 24 mm long fibre with content of 0.2% by the total volume of concrete. It also show that changing basalt fibre length and content enhance not only both tensile and flexural strengths of concrete, but also reduce its compressive strength, workability and air content of concrete, as well as maintain the unit weight and modulus of elasticity values. In this context, the incorporation of basalt fibres within the mixture becomes an important parameter for strengthening concrete in the construction industry.

**Keywords:** Workability; Unit weight; Air entrainment; Compressive strength; Tensile strength; Flexural strength; Modulus of elasticity

### Introduction

During the process of selecting an appropriate material for construction industry, the mechanical properties of material are considered to play a major role in this selection, which depends strongly upon understanding the material microstructure and components. In this context, it's important for engineers to possess a deep understanding of how the microstructure is formed, and how the addition of new materials can influence the engineering properties Adam Warren [1].

To achieve this, the mechanical properties of the concrete should be tested. The mechanical properties of the materials play a significant role in defining the characteristic of the concrete and are defined as the characteristics of materials that are revealed when that material is subjected to mechanical loading. One way of improving the mechanical properties of concrete is by adding fibres to the concrete mixture, and determining their influence on the mechanical properties of concrete, such as: compressive strength, tensile strength, flexural strength, elastic modulus and workability.

Previous investigations on reinforcing concrete containing basalt fibres with different proportions have confirmed the possibility of enhancing the mechanical properties of concrete significantly. Addition of basalt fibres will have significant effect on the mechanical properties of concrete, as they are capable of resisting the high alkalinity environment of concrete, can bond chemically with cement, are a non-corrosive material, have high thermal resistance to heat, and also have a high tensile strength. As a result, basalt fibres are considered to be a promising material to improve the concrete strength.

### Materials and Methods

#### Materials

**Basalt fibres:** The chemical composition of the basalt fibres is given in Table 1. This was derived through Van de Velde K [2] analysis. To

promote bonding between the fibres and the cement it was initially intended to use a cross-linking agent and coat the fibres. A justification of the chosen cross-linking agent will now be discussed. Calcium-Silicate-Hydrate (C-S-H) reaction outputs have been notoriously difficult to predict and model. However, recent advancements in this field [3,4] have opened up the potential integration of chemically compatible additives to hydrated cement gel structures. Shahsaveri [5] and Sakhavand [6] provide a concise summary of current research on integrating polymeric and organic additives into the nano-scale structure of C-S-H. Their paper (in particular pages 85-88) briefly defines and discusses the following as possible options in this regard; Poly(methacrylic acid) (PMA); Poly(4-vinyl benzyl trimethylammonium chloride); Poly(vinyl

Compound	w% in Basalt
	Fibres
SiO <sub>2</sub>	51.6-57.5
Al <sub>2</sub> O <sub>3</sub>	16.9-18.2
CaO	5.2-7.8
MgO	1.3-3.7
B <sub>2</sub> O <sub>3</sub>	--
Na <sub>2</sub> O	2.5-6.4
K <sub>2</sub> O	0.8-4.5
Fe <sub>2</sub> O <sub>3</sub>	4.0-9.5

**Table 1:** Chemical composition of basalt fibres [2].

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alcohol (PVA); Poly(ethylene-co-vinyl acetate) (EVA); Poly(acrylic acid) (PAA); Polyethylene glycol (PEG); 18hexadecyltrimethylammonium (HDTMA); Dimethyl sulfoxide (DMSO); and Methylene blue (MB). PVA in particular shows good bonding potential with the silicates in the C-S-H structure [6]. The accepted bonding model and associated observations describe hydrogen bonding with slip-stick mechanisms under applied loads. This infers that there would be an increase in flexural toughness of the macro-scale material—a beneficial and complimentary property when considering the other constituent materials used within the mix. Having established that PVA has chemical bonding potential with the silicates of the cement hydration products it should be noted from Table 1 that the greatest constituent compound of the basalt fibres is silica ( $\text{SiO}_2$ ).

**Aggregates:** Fine aggregates were well graded with a fifty-fifty mix of coarser sand and finer sand. The coarser sand had 32% passing a 600  $\mu\text{m}$  sieve whilst the finer sand had 97% passing a 600  $\mu\text{m}$  sieve when a grading classification test was performed in compliance with BS EN 1015-1:1999 (BSI, 1999).

A locally sourced coarse aggregate of limestone chippings was selected with a 10 mm nominal maximum size of aggregate. In justification of the selected aggregate size (which deviates from conventionally larger aggregate sizes used in construction practice) it was intended to choose aggregate which was smaller in size than the lengths of basalt fibres used. It was hoped that taking this approach would improve fibre bridging through the concrete composite and encourage fibre fracture failure modes as opposed to fibre pull-out failure modes, thus utilising the full load capacity potential of the fibre—larger aggregate pieces would create discontinuities within the concrete composite.

In essence, the relative sizing between the constituent materials used in the mix was intuitively derived through a ‘scaling of structural strength’ approach as discussed in depth by Bazaant [7].

**Cement:** There are many blends of cement currently available with the most common ones listed in BS EN 206:2013 (BSI, 2013). Ordinary Portland Cement (OPC) CEM I was used which avoided any bonding complexities through additions such as Pulverised Fuel Ash (PFA). The use of OPC ensured sufficient C-S-H silicates would be produced to create hydrogen bonds with the PVA coated basalt fibres.

## Methods

Eleven concrete mixes were cast with different percentages of Basalt fibres lengths and proportions, as shown in Table 2. In order to assess the effect of changing basalt fibre content and lengths on concrete mechanical properties, the research methodology presented in this section comprises two main steps:

**Stage 1:-** Aims to determine the optimum volume fraction of basalt fibre on the mechanical properties of concrete by changing the total basalt fibre content, from mixes (M1-M7) with basalt fibre content varying from 0.2% to 0.3%, and then determine its influence on the mechanical properties of the concrete.

**Stage 2:-** Using the optimum volume fraction of basalt fibre obtained from stage 1, the research is then carried out by changing the percentage content of basalt fibre lengths (12 mm and 24 mm) using mixes (M8-M11) by varying the percentage content of basalt fibre lengths of 12 mm and 24 mm between 0% and 100%. The objective is to identify the optimum basalt fibre length and content that have an influence on the mechanical properties of concrete.

In this research, concrete mixing was carried out in a laboratory at a temperature of 20°C. Both coarse and fine aggregates were stored in dry conditions, and normal tap water was weighed and added to the mixture. All materials were mixed in a concrete mixer with a maximum capacity of 0.06  $\text{m}^3$ . In order to obtain a good concrete mix, the following procedure was adopted.

A mixture of fine aggregates consisting of 50% coarse grey sand and 50% fine red sand was added, with a quarter of the water content. After 60 seconds of mixing, the 10 mm limestone coarse aggregate was added to the mixture with another quarter of the water content for another 60 seconds. Afterwards, the cement, including the basalt fibres at 12 mm and 24 mm, was added. The high range water reducer was then added to maintain the content of the water and to ensure the full distribution of particles. Finally, the mixing continued for another 180 seconds.

Mixing is continued until a uniform and well compacted concrete mixture is obtained. After mixing, casting was performed into two layers for each mix and the mixes were vibrated to remove the air content from the concrete. For each of the eleven concrete mixes, the concrete was cast three times in cubes, steel prisms and steel cylindrical moulds.

After casting, the concrete was left to dry for 24 hours at a laboratory room temperature of 20°C before moulding. The cubes, prisms and cylindrical samples were then kept constantly in water at 20°C and tested after 28 days to determine their mechanical properties.

In practice different standards can be followed for testing the properties of hardened concrete, in this study BS EN 12390-3:2009 was used to determine the compressive strength, BS 12390-6:2009 to determine the tensile strength, BS 12390-5:2009 to determine the flexural strength, and BS 1881-121:1983 to determine the elastic modulus of the concrete. For testing the fresh properties of the concrete, the BS EN 12350-2:2009 slump test was used to determine the workability of fresh concrete, BS EN 12350-6:2000 was used to determine the unit weight of fresh concrete, and BS EN 12350-7:2009 was used to determine the air entrainment of fresh concrete. Each test was performed and repeated three times. For this research, a statistical analysis (ANOVA) was used to investigate the variance of the data at each mix assuming a null hypothesis equals 0.05 (i.e., the confidence interval is 95%). This gives a measure of how the data distributes about the mean, and the difference between mixes. In particular, one-way analysis of variance (ANOVA) is used to determine whether there are any significant differences between the means of independent variables. The individual data and ANOVA results are summarised in Table 3. The null hypothesis assumes that there is no difference between the test data (not significant), whereas the alternative hypothesis assumes that there is a difference between them.

A = Accept the null hypothesis

R = Reject the null hypothesis

## Results and Discussions

### Influence of the basalt fibre on the hardened properties of concrete

**Compressive strength:** Many parameters are known to affect the compressive strength of concrete, most of them being interdependent. Some of the important parameters that may affect the compressive strength of concrete are W/C ratio, properties of the aggregates, air-entrainment, curing conditions, testing parameters, specimen parameters, loading conditions, and test age. Figures 1 and 2 represent

the obtained compressive strength at 28 days for the different concrete mixes M1 to M11. The compressive strength test is carried out according to BS EN 12390-3:2009 and is calculated from an average of three specimens. As can be seen from Table 3, the statistical analysis for the compressive strength shows that changing basalt fibre proportions and lengths variations leads to reject the null hypothesis, and this statically means that there is a difference between the means of the values. Hence changing fibres proportions and lengths has direct and significant effect on the compressive strength of the concrete.

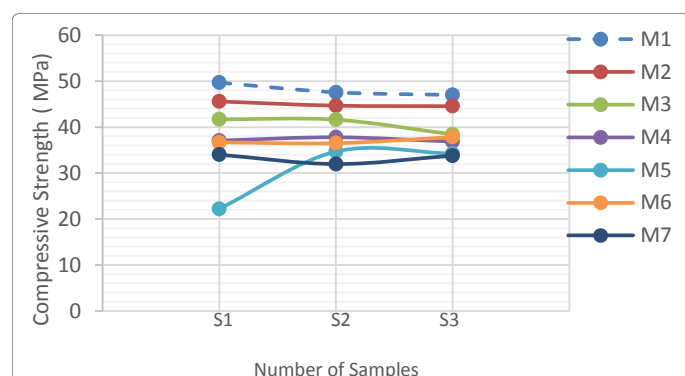
Figure 1 shows the effect of changing basalt fibre content on the compressive strength of the concrete. Using basalt fibres leads to slight reduction in the compressive strength of concrete for all mixes. The compressive strength of the concrete reduces with the increase of the fibre content until 0.26%, after which this value decreased dramatically by 36% when 0.30% fibre content is used. This result is in good agreement with other researchers Paverz Ansari [8] who obtained the same trend, when basalt fibre content increased from 1% to 1.5%. Mustapha Abdulhadi [9] results also showed that the compressive strength of the cubic concrete reduces when increasing the basalt fibre content from 0.9% to 1.2% at 28 days. This considerable concrete compressive strength reduction is attributed to the following factors: Firstly, adding fibres to the concrete mix will reduce the cement paste cohesiveness, which plays a significant role in changing the compressive strength of the concrete. In particular, the compressive strength of concrete depends mainly on the cement matrix, and the effect of enhancing concrete compressive strength is not prominent by adding basalt fibre Jianxun Ma [10]. Secondly, as the fibre content increases, the coarse aggregate is decreased to maintain a constant mixture volume. Decreasing the coarse aggregate content has a direct impact on compressive strength Khaled Soudki [11]. Thirdly, as the volume content of the basalt fibres is added, the

presence of voids caused by the use of higher fibre volume of basalt fibres increases, causing reduction in the compressive strength of the concrete Tehmina Ayub [12].

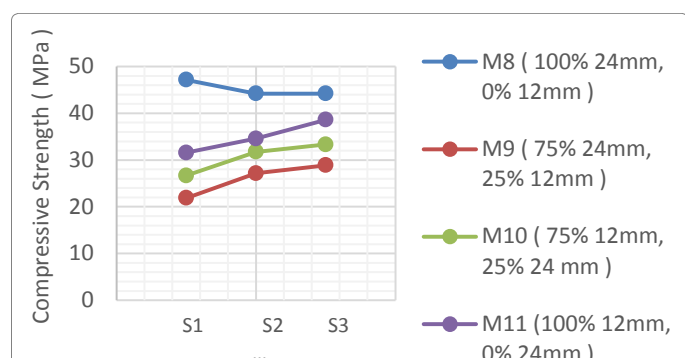
In addition, as seen in Figure 1, the average compressive strength development of concrete mixes M1 – M3 shows these mix proportions meet the strength requirement for high concrete strength, achieving, on average, 41 MPa, although the highest compressive strength value was achieved when concrete contained no fibres in M1, achieving an average strength of 48 MPa. Figure 2 shows the effect of changing basalt fibre lengths on the compressive strength of the concrete for different mixes, M8-M11. The highest compressive strength achieved by all mixes in this series was for mixture M8, containing pure 100% 24 mm basalt fibre, while the remaining mixes, containing a mixture of 24 mm and 12 mm basalt fibres, achieved various strengths ranging from 28-40 MPa. This noticeable improvement in concrete compressive strength when using longer fibres 24 mm is in also in a good agreement with other researchers observation Jerin Johnson, 2016, Palchik P.P [13,14]. Their results show using longer basalt fibres of 24 mm leads to improve the concrete compressive strength significantly. In contrast, it is noticed that using 100% pure basalt fibre of 24 mm and 12 mm, such as in mix M8 and M11, has a greater effect on the compressive strength of the concrete than using a mixture of 24 mm and 12 mm with various percentages, as in M9 and M10, on the concrete compressive strength. This may be attributed to the effect of longer basalt fibres of 24 mm on concrete to create a longer anchorage to hold concrete particles firmly, which will also have a significant effect on the tensile and flexural strength of the concrete.

Figure 3 shows the main effect of the optimum basalt fibre content and length on the compressive strength of the concrete. Mixing basalt fibres with concrete has not enhanced the concrete compressive strength, as concrete is naturally very strong in compression. When concrete is compressed, the interface only serves to transfer compressive stresses from one aggregate to the next; however, under tension, the aggregates try to pull apart. Hence, concrete fails under small stress in tension, but remains strong in compression Rakshita Nagayach [15].

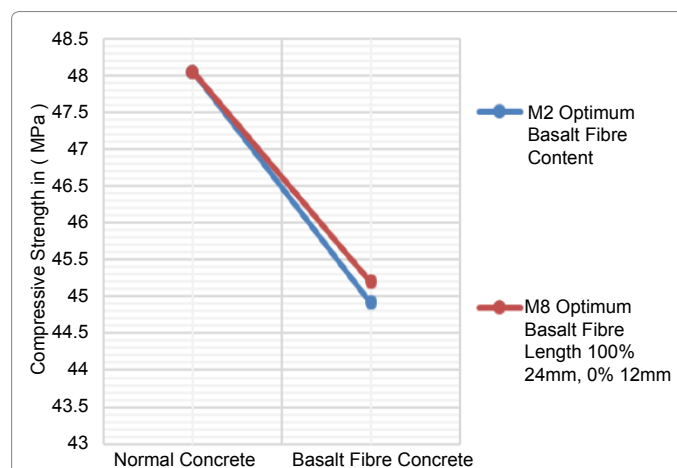
**Tensile strength:** The tensile strength test results for the different concrete mixes, M1 to M7 and mixes M8 to 11, at 28 days, are summarised in both Figures 4 and 5. The statistical analysis for the tensile strength results using Table 3 show that changing basalt fibre proportions leads to accept the hypothesis, while changing its length variations leads to reject the null hypothesis, which means there is a



**Figure 1:** Compressive strength of concrete at different basalt fibre fractions.



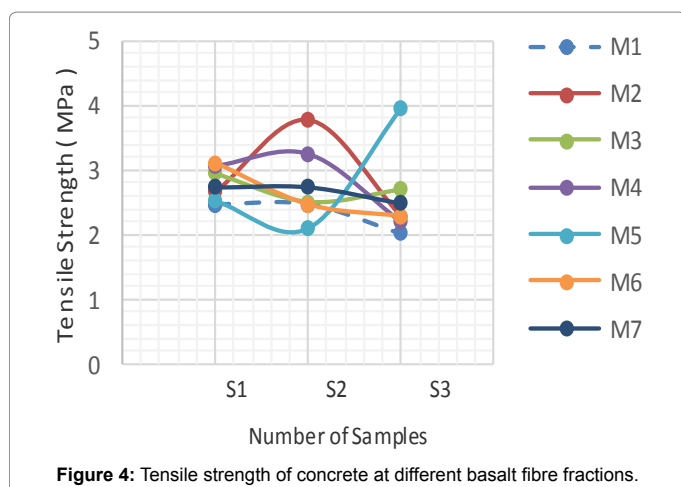
**Figure 2:** Compressive strength of concrete at different basalt fibre lengths.



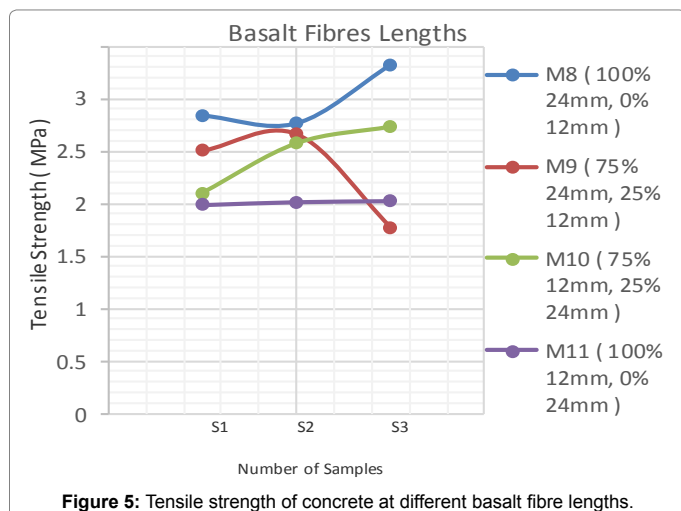
**Figure 3:** Main effect of compressive strength in concrete.

statistical difference between the means of the values when changing the basalt length; however, changing the content has no significance on the tensile strength.

The tensile strengths for different basalt fibre mixtures with different proportions, M1 to M7, and lengths, M8–M11, at 28 days, are shown in Figures 4 and 5. As presented in Figure 4, Mixture 1 with 0% fibre content had an average tensile strength of 2.3 MPa, while all other mixes, apart from M5, achieved a higher tensile strength than the control mixture M1, reaching a tensile strength of 2.8 MPa on average. The optimum tensile strength was achieved when mixing fibre content of M2 0.2% of the total volume of the concrete mix. The test was then carried out by using the optimum basalt fibre content of M2 0.2 % and changing the basalt fibre lengths percentages of 12 mm and 24 mm to precisely determine the effect of changing the length of fibres on tensile strength of concrete. Figure 5 shows that Mixture 8, with 100% 24mm basalt fibre length, achieved the highest tensile strength with an average of 3.2 MPa. The tensile strength of the concrete increased by 17% and 28% versus the control mixture of 0% fibres when using basalt fibre content of 0.2% with 24 mm long fibres, respectively. Tensile strength results obtained by Yihe Zhang [16], Elba Helen George [17] show the same trend, as both authors used basalt fibres with different dosages, and that resulted in improving the tensile strength of concrete. Jianxun Ma [10] experimental work results showed that changing the basalt fibre lengths enhanced the tensile strength of the concrete. This

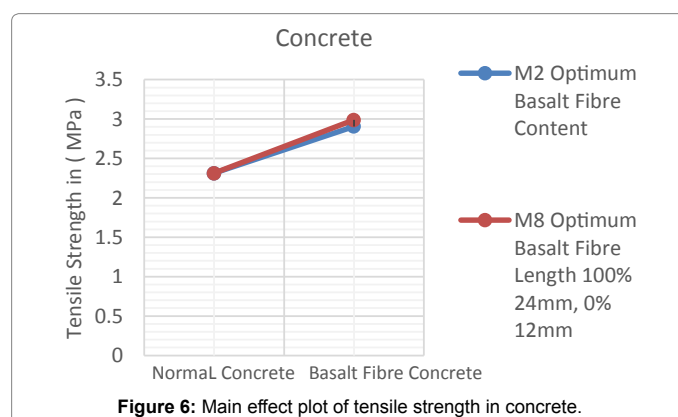


**Figure 4:** Tensile strength of concrete at different basalt fibre fractions.



**Figure 5:** Tensile strength of concrete at different basalt fibre lengths.

increase in is due to the fact that basalt fibres reduced crack growth and consequently led to higher failure loads. The fibres created a bridge through the split portions of the cylinder and prevented the two parts from splitting Khaled Soudki [11]. It is also noticed that longer fibres (24 mm) improved the tensile strength of the concrete much more than 12 mm fibres. This is due to the high tensile strength of these fibres and their ability to form longer bridges to hold concrete particles. On the other hand, Figure 6 shows the effect of fibres in concrete. The tensile strength of concrete is obviously improved by adding basalt fibre, when compared with normal concrete 0% fibres. The splitting tensile strength of concrete increased with increase in the content and length of basalt fibre.



**Figure 6:** Main effect plot of tensile strength in concrete.

Specimen	Basalt	Basalt Fibre	Basalt Fibre
Mark	Fibre	12mm	24mm
	Content %	Length %	Length %
M1(Control Mix)	0%	50%	50%
M2	0.2%	50%	50%
M3	0.22%	50%	50%
M4	0.24%	50%	50%
M5	0.26%	50%	50%
M6	0.28%	50%	50%
M7	0.3%	50%	50%
M8	0.2%	0%	100%
M9	0.2%	25%	75%
M10	0.2%	75%	25%
M11	0.2%	100%	0%

**Table 2:** Details of the concrete mixes.

Description	ANOVA Result
Compressive Strength (28 days)	
Variation in Fibre Content / 50% 12 mm-50% 24 mm	R
Variation in Fibre Lengths / 0.2% fibre content	R
Tensile Strength (28 days)	
Variation in Fibre Content / 50% 12 mm-50% 24 mm	A
Variation in Fibre Lengths / 0.2% fibre content	R
Flexural Strength (28 days)	
Variation in Fibre Content / 50% 12 mm-50% 24 mm	R
Variation in Fibre Lengths / 0.2% fibre content	R
Modulus of Elasticity (28 days)	
Variation in Fibre Content / 50% 12 mm-50% 24 mm	A
Variation in Fibre Lengths / 0.2% fibre content	A

**Table 3:** ANOVA results.



**Flexural strength:** The flexural strength test results for the different concrete mixes, M1 to M7 and mixes M8 to M11, at 28 days, are summarised in both Figures 7 and 8. The statistical analysis for the flexural strength results using Table 3 show that changing basalt fibre proportions and length variations leads to reject the null hypothesis, which means there is a statistical difference between the means of the values; hence, changing fibre proportions and lengths has a significant effect on the flexural strength of the concrete. The test for the flexural strength development of concrete was also carried out at different ages of seven days, 28 days, 84 days, and 168 days using the optimum basalt fibre that has influence on the flexural strength of the concrete. A three point bending test was used using a  $150 \times 150 \times 750$  mm prism. The flexural strength of the concrete under the three point bending test was calculated using the following formula:

$$\sigma = \frac{3FL}{2bd^2} \quad (1)$$

Where:

$F$  is the load (force) at the fracture point (N)

$L$  is the length of the support span

$b$  is width

$d$  is thickness

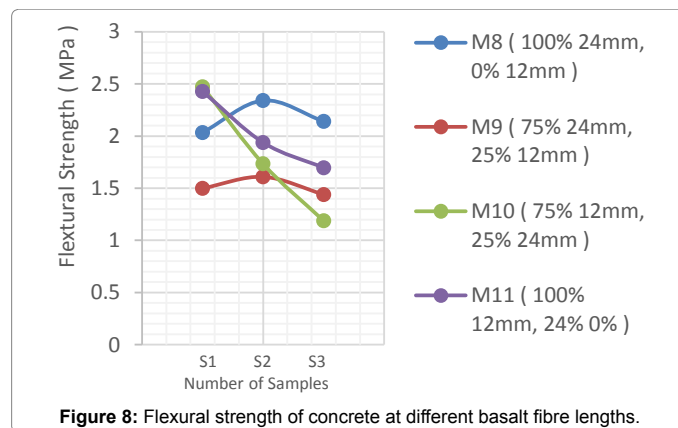
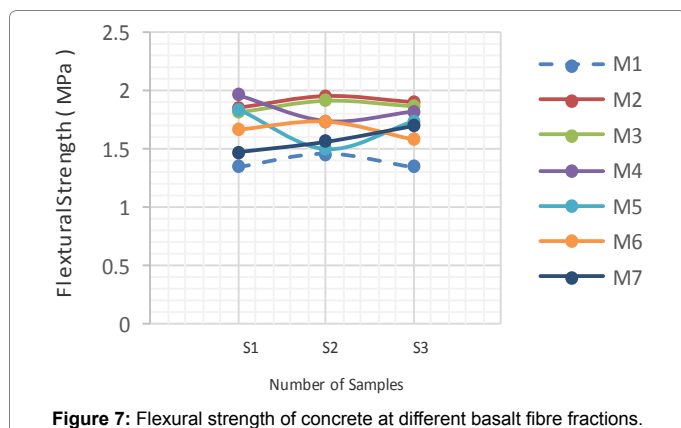
$\sigma$  is the flexural strength in (MPa)

The flexural strength development of concrete mixed with different proportions of basalt fibre is illustrated in Figure 7. It is evident that increasing basalt fibre content increases the flexural strength of the concrete when compared to the control mixture, M1, 0% fibre content. The optimum basalt fibre content was achieved when using basalt content of M2, 0.2%, while mixture M1 0% basalt fibre achieved the lowest value. The flexural strength ranged from 1.3 MPa to 2 MPa when changing the basalt content, while this value increased when changing the length of the fibres, ranging from 1.5 MPa to 2.5 MPa as can be seen from Figure 8. The Figure 8 also shows that the flexural strength of the concrete increased sharply when using basalt fibre content mixtures of M2, M3 and M4, 0.2%, 0.22%, 0.24%, respectively, at 28 days and then gently decreases afterwards to give a lower strength values when using contents of M5, M6, and M7, 0.26%, 0.28%, and 30% respectively. The increased number of fibres that cross the crack surface is one of the main reasons to increase the flexural strength of the concrete, as they reduce the crack opening. Kayali [18], Zollo [19] also reported that the presence of basalt fibre with different contents has a contribution

to the flexural strength of concrete. The test was then carried out by using the optimum basalt fibre content of M2, 0.2 %, with changing the basalt fibre lengths percentages of 12mm and 24mm, to precisely determine the effect of changing the length of fibres on flexural strength of concrete. According to Figure 8, Mixture 8, with 100% 24mm basalt fibre length, consistently displayed the highest flexural strength with an average of 2.3 MPa. The differences in the flexural strength due to the change of the length of the fibres were considerable and average values of 2.3 MPa, 2.1 MPa and 1.7 MPa were recorded when using different lengths of fibres. In contrast, using longer fibres, such as 24 mm, resulted in increasing the flexural strength of fibres, as can be seen from Figures 7 and 8, but, when using a blend of 12 mm and 24 mm fibres, the flexural strength remained the same, achieving an average value of 2 MPa. This is perhaps because of the ability of the longer fibres that cross the crack region to reduce the concrete cracks more significantly than the short fibres, as they are able to transfer load more efficiently, and also redistribute stress. The longer fibres take to transfer stress, the longer time it takes for the crack to develop; hence, the higher the tensile and flexural strength that can be reached. The same result was achieved by Jianxun Ma [10], who concluded that increasing the fibre length and content will increase the flexural strength of concrete.

In general, the flexural and tensile strength of the concrete reinforced basalt fibre are increased with the increase dosage and length of the basalt fibre. When the fibre content is 0.2% by total volume, which is equal to  $0.27 \text{ kg/m}^3$  and the basalt fibre length is 24 mm, It appears that for mixes with 0.2% of fibre content and length of 24 mm achieved an overall higher flexural and tensile strength in comparison to other mixes investigated in this analysis. As a result, the use of basalt fibres is regarded as a strengthening material for the concrete, and can have a significant effect on the concrete structures. On the other hand, Figure 9 show the main effect of fibres in the flexural strength of concrete. From the graph, it is clear that the flexural strength of concrete is increased by adding basalt fibre, when compared with normal concrete 0% fibres. The flexural strength of concrete increased with increasing the content and length of basalt fibre. In Particular, mixing concrete with 24 mm basalt fibre length will have a larger effect on the flexural strength of the concrete when compared with using different fibre lengths.

The flexural strength development of concrete at different ages of seven days, 28 days, 84 days and 168 days using the optimum basalt fibre mixture (M8) that has influence on the flexural strength of the concrete is illustrated in Figure 10. The Figure 10 shows that the flexural strength of the concrete increases sharply when increasing the age of the test, reaching its minimum value at seven days, and maximum value at 168 days. This is due to the hydration of cement, as well as the chemical

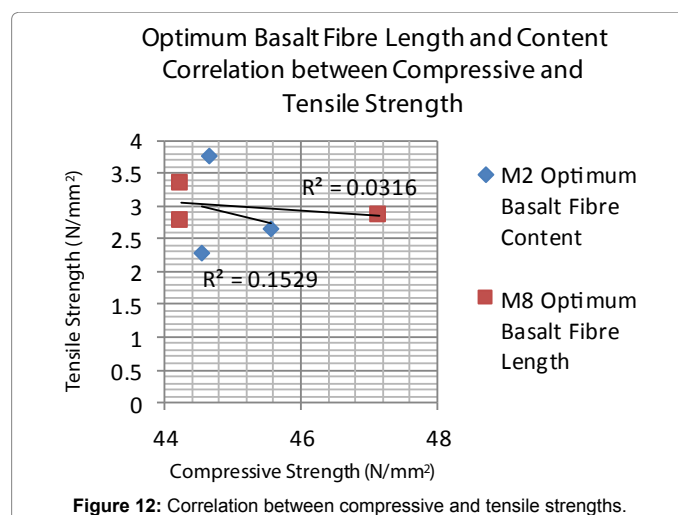
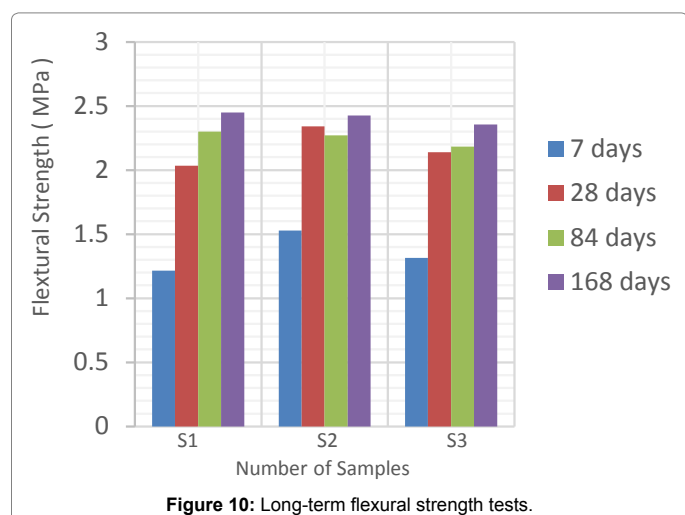
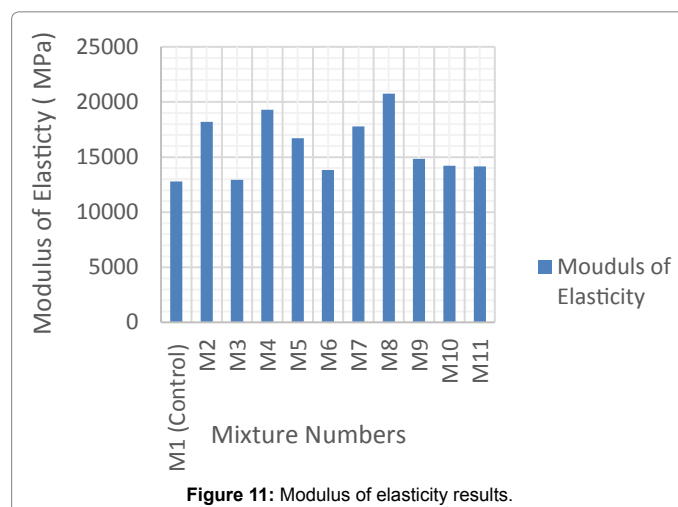
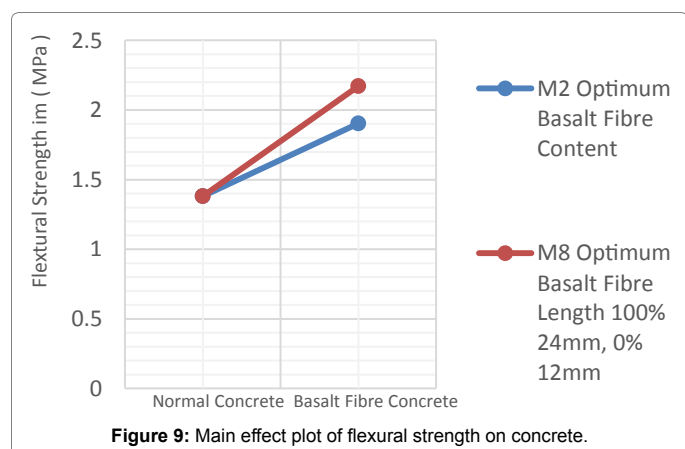


reaction on the concrete, as they require time to formulate, which helps concrete gain more strength. The presence of basalt fibres also plays a major role, as they enhance the flexural strength of the concrete. Using the same figure, it can be seen that there is a big difference in concrete strength at the different testing ages of seven days, 28 days, 84 days and 168 days. The lowest values were registered at seven days, with similar average values of 2.2 MPa recorded after 28 and 84 days, while the largest strength average values of 2.4 MPa were recorded after 128 days. The rate of the flexural strength increase with days is considerably fast, ranging, on average, from 1.3 MPa to 2.4 MPa. In other words, the flexural strength development between seven and 168 days was not only influenced by the presence of basalt fibres, but also by the curing time of the concrete.

**Modulus of elasticity:** The statistical analysis for the modulus of elasticity results using Table 3 show that changing basalt fibre proportions and length variations leads to accept the null hypothesis, which means there is no statistical difference between the means of the values; hence, changing fibre proportions and lengths has no significant effect on the modulus of elasticity of the concrete. The elastic modulus is calculated within elastic range in its ascent in stress-strain curve and is expressed in function of compressive strength of concrete. Figure 11, shows the elastic modulus for all mixes. Based on the graph in Figure 11, the modulus of elasticity for all mixes ranged from 12000 MPa to 21000 MPa. Mixture M8 (100% 24 mm basalt fibre with 0.2% content) had the highest modulus of elasticity, while Mixture M1 (the control mixture)

had the lowest modulus of elasticity. Basalt fibres slightly increased the modulus of elasticity of the concrete. This may be attributed to the effect of fibres to enhance the concrete density, as a result improving the concrete toughness and resistance to deformation. The modulus of elasticity achieved by M2, M3 and M4 was 29%, 1.15%, and 33% above of the control mixture, no fibres, respectively. The greatest increase in the modulus of elasticity occurred between M3 and M4, followed by a gradual decrease from M4 to M6. The general value of the modulus of elasticity mixed with different fibres increased and decreased slightly compared to the control mixture. This indicates that basalt fibre had not contributed majorly to the modulus of elasticity of the concrete. This result is possibly due to the strong ability of concrete to resist the compressive strength load when it is applied, also due to the inability of fibres to resist the vertical load when applied. Ramakrishnan [20] also reported that basalt fibre has no effect on the modulus of elasticity of concrete.

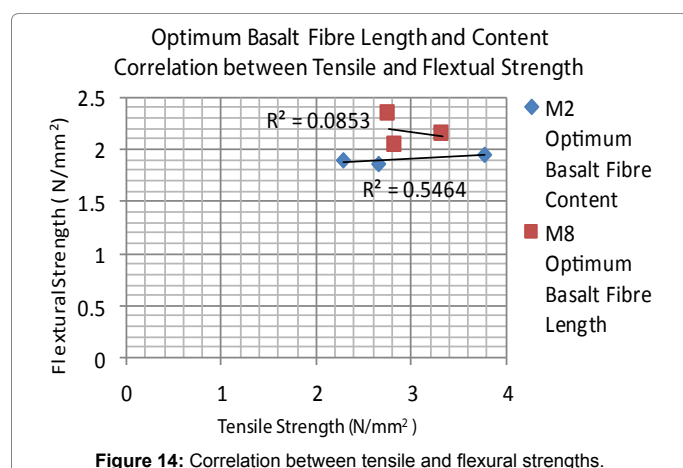
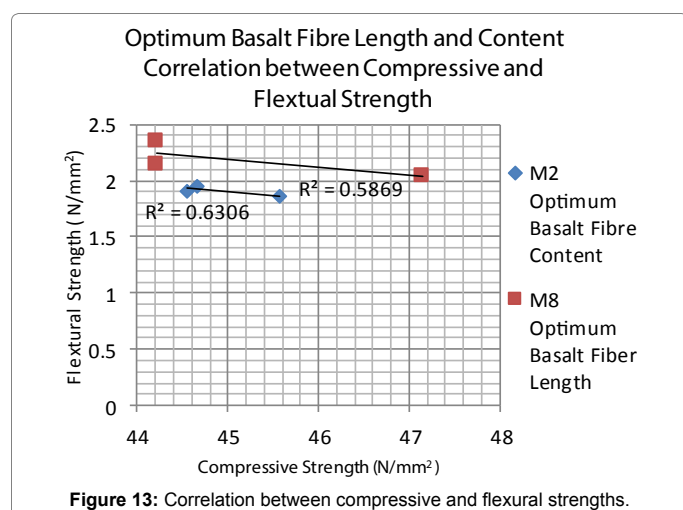
**Correlation between the compressive strength and tensile strength:** The relationship between the compressive and tensile strengths is presented in Figure 12. No correlation can be seen between those two concrete properties, as found  $R^2$  values were 0.03 and 0.15 for mixing concrete with the optimum content and optimum length, respectively. This may be attributed to the use of different basalt mixtures between M2 and M8. For M2 mixture, a blend of 50% of 12



mm and 50% of 24 mm basalt fibre lengths was used, while, for M8, only 100% 24 mm basalt fibre length was used. As a result, this affected the relationship between the two concrete properties.

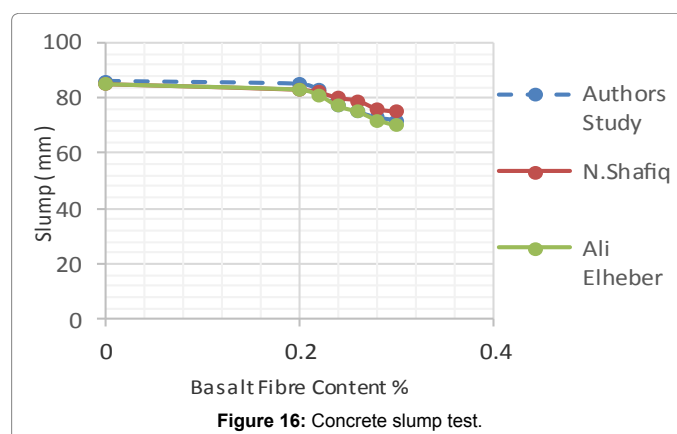
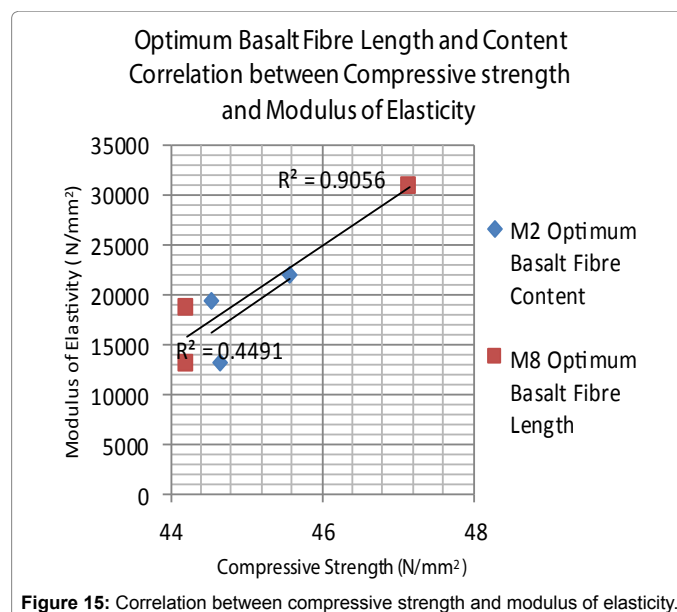
**Correlation between the compressive strength and flexural strength:** Figure 13 shows the correlation between the influence of basalt fibres at optimum length and content on concrete compressive and flexural strengths. There seems to be a strong correlation between using optimum concrete length and content, M2 and M8, as found from the R<sup>2</sup> coefficient values being 0.6 and 0.5, respectively. In addition, all data points in the graph seem to fit approximately in a straight line, which shows a linear and strong relationship between these two concrete properties.

**Correlation between the tensile strength and flexural strength:** The relationship between the concrete tensile and flexural strength is presented in Figure 14. No correlation can be seen between those two concrete properties, as found R<sup>2</sup> values were 0.0853 and 0.5 for optimum basalt length M8 and optimum basalt content M2, respectively. However, by using the graph, the data points seem to fall in the same range between tensile strength values of 2.3 MPa–3.6 MPa and flexural strength values ranging from 1.8 MPa–2.3 MPa. It is also noticed that higher values were recorded when using optimum basalt fibre M8, as 100% longer fibre 24mm was used, which increased the values of the tensile and flexural strengths, respectively.



**Correlation between the compressive strength and modulus of elasticity:** In Figure 15, the relationship between the compressive strength and modulus of elasticity for optimum basalt fibre length (M8) and content (M2), as well as the corresponding best fit linear line, are shown. As in the case of the correlation between the compressive and modulus of elasticity, it is noticed that there is a positive relationship between the two variables, as their corresponding R<sup>2</sup> values are 0.9 and 0.4, respectively; however, the distribution of the data points is relatively high. There seem to be no consistency in increasing and decreasing values between the two parameters by using Mixtures M8 and M2, which indicates that there is no correlation between the compressive and modulus of elasticity of concrete when mixed with different mixtures.

**Workability:** From the results presented at Figure 16, the target slump values for all basalt fibre mixtures ranged from 85 mm to 70 mm. It is also noted that the slump value reduced with increasing the basalt fibre content. These results were also obtained by Ali Elheber [21], N. Shafiq [22] and can be seen plotted in Figure 16. This is mainly because basalt fibre has the ability to absorb certain moisture when added to the concrete, causing a reduction in the slump of the concrete, which also improves the concrete permeability, as it reduces the pore gaps in the concrete microstructure Jianxun Ma [10]. On the other hand,



increasing the content of the fibres in concrete enhances the mass added to the mixture, which leads to a decrease in the flow ability of the concrete Tumandir [23]. From the test result observed, there was no aggregate segregation and full homogeneous mix was observed from the test. Also, the result showed that adding different basalt fibre content between 0% to 0.30%, had a major effect on the concrete slump. In general, the concrete remained in good condition and remained workable after the addition of basalt fibres.

**Unit weight:** Figure 17 shows the mean density recorded by each concrete mixture, from M1 to M7. The density of the specimens ranged from 2400 to 2415 kg/m<sup>3</sup>. This lies within the range of 2200 to 2600 kg/m<sup>3</sup>, specified as the density of normal weight concrete Neville [24]. The graph shows that, as the content of the basalt fibre increases, there is a slight increase in the unit weight of the concrete due to the fact that basalt fibres are the lightest component in the concrete mixture and their effect on the concrete unit weight can hardly be noticed. This is similar to the results obtained by Thumandhir [23], who indicated that basalt fibres have little effect on the concrete unit weight, as can be seen from Figure 17.

**Air entrainment:** The air content of the basalt fibre-reinforced concrete ranged from 3.7% to 4.8%, as shown in Figure 18. The control mix (M1) achieved the highest rate of air content, as expected, while M7 with basalt fibre content of 0.30% recorded the lowest air content in concrete. The air content results indicate that, as the basalt fibre content increases (M1-M7), the air content decreases. This is due to the ability of fibres to fill voids in concrete when higher content of fibres

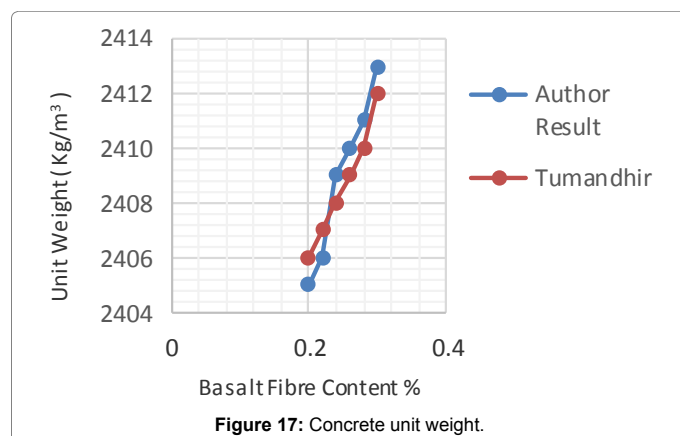


Figure 17: Concrete unit weight.

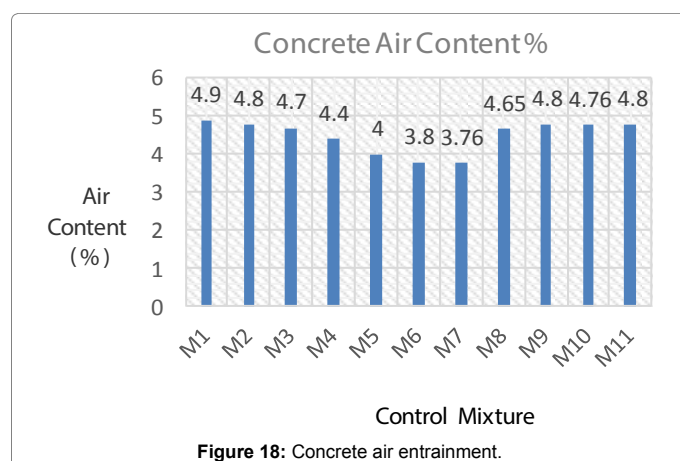


Figure 18: Concrete air entrainment.

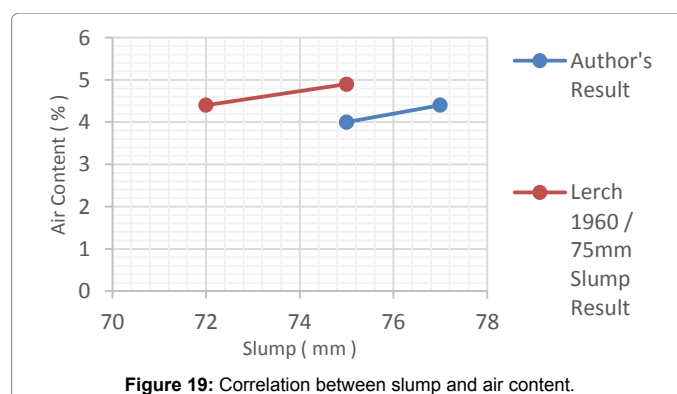


Figure 19: Correlation between slump and air content.

is added to the concrete mixture. This result was also achieved by O. Gencil [25], who found that the void content of the concrete reduces with increasing the fibre content. It is also evident that the concrete mixture with longer fibre length (100% 24 mm), Mixture 8, had slightly lower air content values than the concrete with shorter fibres (M9-M11). Air entraining provides an additional benefit to concrete mixes. This is mainly because it has a major influence on enhancing the workability of the concrete as it acts as air bubbles, which reduce the friction between the cement and the surrounding aggregate. Therefore, this reduces the interlocking and cohesion between the particles and also reduces the content of the water in concrete; hence, improving the concrete's workability. To understand this phenomenon, Figure 19 is given to illustrate the correlation between the workability and the air content in concrete. By using Figure 19, the graph shows that, as the air content in the concrete increases, the slump of the concrete also increases. And, when the air content value is between 4-5% of the total concrete volume, the corresponding slump is approximately 75 mm. This result was achieved by both Lerch [26] and myself, as can be seen from the graph below. As mentioned earlier, it is noted that, when more basalt fibre content is added to the concrete mixture, the values of the slump and air content decrease. In contrast, the relationship between the slump and air content is completely different, as there is a linear relationship between the two features, as can be seen from Figure 19. By using the same Figure 19, there was a slight difference between the author's and Lerch's values; this is due to the difference between the aggregate sizes that were used by the authors. In general it can be said that the properties of fresh concrete can be significantly improve by the addition of fibre, especially when controlling air content, unit weight and workability.

## Conclusion

In this paper, the fresh and the hardened mechanical properties of concrete were investigated using different lengths of basalt fibres of 24 mm and 12 mm. This comprehensive investigation used analytical software, ANOVA, to analyse the results, and validated these values against the results obtained from the laboratory samples. The presented data indicate that the optimum basalt fibre content to have the most influence on concrete is 0.2% by the total volume of concrete, using basalt fibre length of 24 mm. It also show that changing basalt fibre length and content enhanced not only both tensile and flexural strengths of concrete, but also reduced its compressive strength, workability and air content of concrete, as well as maintain the unit weight and modulus of elasticity values. These results were also confirmed by using ANOVA software, as the analysis software indicated that change of the proportional and length of basalt fibre has significant effect on the tensile and flexural strengths, but has no major effect on the modulus



of elasticity and compressive strength. A reasonable correlation between compressive strength and flexural strength was noticed, as well as between compressive strength and the modulus of elasticity for optimum basalt fibre length and content.

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