HIGH PERFORMANCE RECYCLED AGGREGATE CONCRETE INCORPORATING MICRO SILICA AND SYNTHETIC MACRO FIBRE

by

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ABSTRACT

The continuous global demand for infrastructure due to persistent increase in population growth implies that more aggregate and cement would be required in concrete production. This would eventually lead to more extraction and depletion of natural resources and increased carbon emission. The aim of this research work was to develop high performance concrete using recycled coarse aggregate, microsilica, and synthetic macro fibre with the object to boost higher use of recycled coarse aggregate in the construction industry.

Concrete was designed for 28-day compressive cube strength of 50MPa, high workability (60-180mm) and a constant water-cement ratio of 0.39. Microsilica was incorporated up to 20% of cement content at 5% intervals, while the natural coarse aggregate substitution by recycled coarse aggregate ranges between 0 - 100% at 25% interval. Workability, compressive cube strength, tensile splitting strength, flexural strength, static elastic modulus, and water permeability tests including fatigue assessment were conducted respectively.

Results confirmed that, the incorporation of 15% microsilica with 50% recycled coarse aggregate fraction produced 28-day compressive cube strength which exceeds the characteristics and target mean compressive cube strength of the control mix which are 50MPa and 63.1MPa respectively. The result suggests that there is a potential to increase the optimum fraction of recycled aggregate from 30-50% in concrete.

DEDICATION

This thesis is dedicated to my family and the entire people that have been part of my self-funded academic life at the University of Birmingham close to a decade.

You are the pride of human existence.

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List of Abbreviations

BLT	Ballast-less track
BRE	Building Research Establishment
CFP	Collated fibrillated polypropylene
CSH	Calcium silicate hydrate
FA	Fly Ash
GGBS	Ground Granulated Blastfurnace Slag
HPC	High performance concrete
PFA	Pulverished Fly Ash
RA	Recycled aggregates
RCA	Recycled coarse aggregate
SEM	Scanning Electron Microscope
SSD	Saturated surface dry

1 INTRODUCTION

1.1 Background

The increasing demand for infrastructure due to continuous rise in population growth, and high rate of urban drift as a result of industrialisation and urbanisation has led to more consumption of concrete which is the second most widely consumed resource in the world after water (Ecocem, 2011) and also the most widely used construction material (Crow, 2008) in the last few decades. The continuous global demand for concrete implies that more aggregate and cement would be required in the production of concrete thereby leading to more extraction, depletion of deposits of natural gravel, limestone, and increased CO_2 emission from quarrying activities and production of cement. Cement is a very significant source of global carbondioxide (CO_2) emissions, contributing approximately 5% of global anthropogenic CO_2 emissions Worrell et al. (2001).

Generally, aggregates account for a huge proportion (60-75%) of the overall volume of concrete (Mummaneni, 2011), which implies that partial substitution of natural aggregate with recycled aggregate would lead to reduction in construction cost and carbon footprints of the construction industry. Although, concrete is characterised by very advantageous features ranging from cost effectiveness, durability, outstanding compressive strength, and availability, the continuous use of conventional concrete, (that is concrete produced with virgin aggregates and ordinary Portland cement) has proved to be very unfriendly to the environment as a result of depletion of the natural resources, growing disposal problems and huge energy consumption in quarrying activities. With reference to this ongoing trend and in order to achieve sustainable development goal of environmental preservation in the construction industry, better initiative to mitigate the associated problems emanating from the use of virgin aggregate and Portland cement should be considered. These initiatives which include the use of mineral admixtures like microsilica and debris from construction and demolition waste generally known as recycled aggregate should be widely encouraged. "This represents the most desirable method of ensuring a closed life cycle for concrete as a construction material" (Barra and Vazquez, 1998), thus leading to maximization of both economic and environmental benefits. The associated benefits from these initiatives would therefore enable the present generation to leave a sustainable legacy behind for the future generations.

The concept of using recycled coarse aggregate as partial substitute for virgin coarse aggregate in concrete is not new to the construction industry and significant progress has been made over the past years since recycled aggregate properties were first investigated by Gluzhge in 1946 due to modern sustainable concrete technology. This eventually led to the current use of recycled coarse aggregate for non-structural concrete applications such as embankment fills, low-grade concrete production, coarse materials for road sub-base, paving blocks, drainage etc. In spite of many research studies and findings, there is urgent need to improve the engineering properties of recycled coarse aggregate concrete and this would help to reduce the current high level of uncertainty associated with the structural use of the material in concrete production.

The use of synthetic macro fibre and mineral admixture (i.e. microsilica) could enhance the physical and engineering properties of recycled aggregate concrete. These interactions would be investigated with a view to evaluate the potential to increase the optimum fraction of recycled coarse aggregate in concrete from the currently recommended 30% level of replacement (BS 8500-2) without any cause for concern.. There is a clear distinction between the conventional concrete (Natural aggregate & Portland cement) and concrete incorporating mineral additive, and chemical admixture otherwise called High Performance Concrete. By definition, High performance concrete (HPC) denotes concrete that is capable of satisfying special performance conditions which cannot be achieved with conventional concrete. According to Holland (1993), "high performance concrete possesses high strength, high durability, increased workability, high modulus of elasticity, and low permeability". These characteristics are derived from the benefits of using mineral admixtures in combination with chemical admixtures.

The clear distinction between high performance concrete and conventional concrete are not restricted only to strength increase, but also include the full relationship between stress and strain. The benefits of high performance concrete will be highlighted and an attempt will be made to investigate whether performance issues such as porosity, poor workability, and low strength associated with recycled coarse aggregate can be mitigated by incorporating microsilica and fibre in recycled aggregate concrete. Microsilica contributes both physically and chemically in concrete mix. The physical contribution occurrs through its action as nucleation sites which reduces the average size of pores present in cement paste thereby enhancing concrete properties while the chemical contribution takes place mainly by acting as an efficient pozzolanic material which enables even distribution and higher volume of hydration products.

Although the initial cost of high performance concrete is higher than the cost of conventional concrete, the long term cost-benefits outweight higher cost at initial procurement. Concrete is a heterogeneous material comprising fine aggregate, coarse aggregate, potable water, and the binder known as cement), and the presence of coarse aggregates contributes more to the heterogeneity. The interface between the surfaces of aggregate and cement is weak and this is responsible for the low concrete strength. The incorporation of micro silica in concrete mix tends to shift the heterogeneity of concrete from full heterogeneity to more homogeneity with a very significant improvement in terms of durability and strength. Godman and Bentur (1989), and Song et al. (2007) suggested that porosity of the interfacial transition zone between aggregate and cement matrix in fresh concrete could be lowered with the incorporation of micro silica, and this is responsible for the provision of the required microstructure for a strong Interfacial Transition Zone (Pauw and Lauritzen, 1994).

Most researchers incorporated micro silica as partial replacement for cement in concrete mix while this research work incorporates micro silica as an addition with the intent to evaluate the optimum required addition that would produce the best significant result in terms of strength, durability, and workability..

1.2 Research aim and objectives

1.2.1 Aim

The major aim of this research is to develop a High Performance Concrete (HPC) using recycled coarse aggregates as substitute for natural coarse aggregate, synthetic macro fibre, and mineral admixture (micro silica) in order to improve the engineering properties of recycled aggregate concrete with an additional goal to boost the potential of increasing its uses from the recommended 30% level by BS 8500-2 and some past researchers. Adequate factual scientific information are thereby required to establish the mechanical and physical characteristics of high performance concrete incorporating these aforementioned materials.

1.2.2 Objectives

The objectives are to;

1) determine fresh and hardened properties of concrete incorporating various percentage of recycled coarse aggregate content;
2) assess the impact of 54mm Forta-Ferro synthetic macro fibre dosage on the physical and mechanical properties of concrete produced in (1) above;
3) evaluate the effect of addition of mineral admixture (microsilica) and chemical admixture (superplasticiser) on concrete produced in (2) above;
4) determine the optimal use of microsilica required to achieve higher performance in concrete produced in (3) above;
5) assess the durability of concrete produced from in (2) and (3) above in terms of water permeability;

6) evaluate the flexural fatigue performance of fibre reinforced concrete incorporating microsilica which produced the optimal effect in (BS-EN-12390-4) above.

The outcome of this research will provide better understanding about the properties of recycled aggregate concrete produced from the aforementioned materials and contribute greatly in ensuring that the construction sector increase the use of recycled coarse aggregate beyond the current recommendation. This research is also limited to the use of recycled coarse aggregate as a replacement for natural coarse aggregate, synthetic macro fibre and microsilica as an addition to cement respectively.

1.3 Significance of Research

The following listed are potential benefits from this research work to the construction industry and the environment. These are;

1) Reduction of pressure on landfills from construction and demolition debris;
2) Potential to increase the use of recycled coarse aggregate beyond the maximum recommended 30% (BS 8500-2);
3) Conservation of natural resources through reduction in the use of natural coarse aggregate for concrete work;
4) Mitigation of performance issues like high porosity, poor workability, low strength, and high water absorption associated with recycled aggregate by incorporating microsilica (mineral admixtures) in the concrete mix;
5) Potential application of recycled coarse aggregate in structural concrete.

1.4 Thesis Structure

This thesis consists of eight chapters as itemised in the table of contents in line with the objectives of the research mentioned earlier.

Chapter 1 is the introductory chapter which provides full background to the research problems that necessitated this research work. The aim and objectives of the research are discussed with the potential benefits of the findings to the construction industry and the environment. The structure of the thesis and list of publications by the author are reported under this chapter.

Chapter 2 reviews past related research findings in the use of recycled coarse aggregate (as a partial and full substitute for natural coarse aggregate in concrete), microsilica and synthetic macro fibre. Their respective impact on the physical and engineering characteristics of concrete are discussed in detail. Various types of rail track concrete system which is the intended application for this research were discussed and the existing development and identified knowledge gap were reported.

Chapter 3 provides the exact methodology employed in order to achieve the set aim and objectives of the research mentioned in the introductory chapter.

Chapter 4 describes the details of the experimental work on the effect of synthetic macro fibre inclusion on recycled aggregate concrete. The results, discussion and summary of findings are also presented.

Chapter 5 presents the outcome of the assessment of the impact of microsilica addition in enhancing the performance of fibre reinforced recycled aggregate concrete produced in chapter 4. Detailed results, discussions and summary of findings are given under this chapter.

Chapter 6 reports the results, discussions and summary of findings on the optimised use of microsilica in fibre reinforced recycled aggregate concrete produced in chapter 5.

Chapter 7 discussed the flexural fatigue assessment of high performance concrete incorporating recycled coarse aggregate and synthetic macro fibre under cyclic loading.

Chapter 8 summarises all the major conclusions from the research findings and recommends areas that require further investigation in the future.

1.5 List of Publications

As a direct outcome from this research, the following publications were produced.

TIJANI, A., YANG, J. & DIRAR, S. 2015. Enhancing the Performance of Recycled Aggregate Concrete with Microsilica. International Journal of Structural and Civil Engineering Research, 4, 347-353.

TIJANI, A., YANG, J. & DIRAR, S. 2015. Optimum use of microsilica in high performance Concrete with Microsilica. International Journal of Civil and Structural Engineering, 2, 297-301.

TIJANI, A., YANG, J. & DIRAR, S. 2014. High performance concrete using recycled aggregate, Microsilica and synthetic macro fibre. Proceedings of the International Conference on Advances in Civil, Structural and Mechanical Engineering, 231-234.

2 LITERATURE REVIEW

2.1 Introduction

The review of past related studies is presented and discussed in this chapter with the focus lying on the effect of recycled coarse aggregate, synthetic macro fibre, and micro silica on fresh and hardened concrete properties. Although research has been undertaken to assess the suitability of recycled coarse aggregate (RCA) as a substitute for virgin coarse aggregate in concrete, few attempts have only been made to investigate the synergy between microsilica and synthetic macro fibre addition in recycled aggregate concrete for high strength structural concrete application. Most of the researchers incorporated microsilica as a partial substitute for cement in the concrete mix while few researchers considered addition of microsilica. This investigation will examine the contribution of synthetic macro fibre together with the incorporation of microsilica which has been reported by some researchers to have the tendency to improve the engineering properties of concrete. Various findings and contributions by previous researchers are reviewed with a view to summarise the latest development and identify the knowledge gap.

2.2 Physical Properties of Aggregate and Concrete

2.2.1 Density and Water Absorption

Recycled coarse aggregate posseses low density, high porosity and high water absorption (Poon et al. (2007). This drawbacks lead to low a utilization of recycled coarse aggregates in structural concrete. Rao et al. (2011) investigated the behaviour of recycled aggregate concrete under drop weight impact load and reported that the density and specific weight of recycled coarse aggregate decreases as the recycled coarse aggregate content in the concrete mix increases. This effect was linked to the light weight & porous mortar attached to the parent aggregates. Similarly, Sagoe-Crentsil and Brown (1998) reported that the density of recycled aggregate concrete is lower compared with the density of the conventional concrete due to the porous nature and less dense residual mortar lumps adhered to the surfaces of the recycled aggregate. An assessment of the performance of recycled aggregate concrete revealed that the density was about 3 - 10% less than the conventional concrete while the water absorption was about 3 - 5 times more than the corresponding virgin aggregate (Limbachiya et al., 2004). This observation was associated with the attached cement paste on the recycled coarse aggregate.

Hurley and Bush (2007) reported that the water absorption of recycled aggregate was about 6 - 12 times higher compared with natural aggregate due to the presence of residue mortar adhered to original aggregate. Recycled aggregate has about 4 - 5 times higher water absorption rate than the virgin coarse aggregate (Kikuchi et al., 1993). These results were corroborated by the findings by Forster et al. (1994), Parekh and Modhera (2011), and Wang et al. (2011) respectively. Morel et al. (1994) reported high water absorption rate between 5.5% - 7% for recycled aggregates recovered from demolished structures which contains brick, stone, concrete and ceramic. Similar findings were reported by Rashwan and AbouRizk (1997) with recycled coarse aggregate having higher water absorption rate between 4 - 7% than conventional coarse aggregate and this was more pronounced in older parent concrete.

Chan (1998) investigated the use of recycled aggregate in shortcrete and concrete with a conclusion that the water absorption for recycled aggregate concrete exceeds that of natural aggregate due to presence of attached mortar. An investigation into durability of recycled aggregate concrete conducted by Levy and Helene (2004) revealed that recycled aggregate concrete had about 6 – 10% more water absorption rate than virgin aggregate as the percentage content of recycled coarse aggregate increases in the mix, while Corinaldesi et al. (2001) recorded about 8% (four times) more water absorption rate in recycled aggregate recovered from concrete rubble than natural aggregate. Although irrespective of the high water absorption, the performance of recycled coarse aggregate was similar to natural aggregate.

Salem and Burdette (1998) investigated the use of crushed old laboratory concrete samples as recycled coarse aggregate to substitute natural coarse aggregate. The water absorption rate for the recycled coarse aggregate was about 4.7% more than the natural coarse aggregate. This result was attributed to low density of recycled aggregate. Recycled aggregate concrete has a higher water absorption rate than natural aggregate concrete due to porosity which increases with increasing recycled aggregate content (Zaidi, 2009). Zhang and Ingham (2010) also recorded lower dry density and higher water absorption rate in recycled aggregate concrete with reference to the conventional concrete.

2.2.2 Workability

2.2.2.1 Effect of recycled coarse aggregate

Recycled coarse aggregate concrete have lower workability than concrete made from conventional coarse aggregate (Limbachiya et al., 2004; Topcu and Şengel, 2004). This observation confirmed the results obtained by (Fraaij et al., 2002; Kenai et al., 2002; Poon et al., 2004a). Etxeberria et al. (2007b) studied the effect of recycled coarse aggregates production process and quality on the properties of recycled aggregate concrete. Result findings showed that the workability of recycled aggregate concrete is lower than natural aggregate concrete as a result of the absorption capacity of the recycled aggregate.

Patil et al. (2013) evaluated the physical properties of concrete produced from recycled coarse aggregate. Results indicate higher workability for virgin aggregate concrete as against concrete incorporating 100% recycled aggregate. The low workability recorded was attributed to high rate of water absorption associated with recycled coarse aggregates, and this observation was corroborated by findings from Zaidi (2009), that workability of recycled aggregate concrete reduced in comparison to virgin aggregate concrete due to higher absorption rate of the former. Yang et al. (2010) investigated the use of recycled concrete aggregate and crushed clay bricks as a replacement for natural aggregate in concrete. The findings showed that workability decreased with increasing recycled aggregate and crushed clay brick contents in the concrete mix. The result was attributed to the porous texture of the aggregate material and attached concrete mortar.
Adnan et al. (2007) investigated the effects of different percentage substitution of natural aggregate by recycled aggregate on concrete and reported that, the higher the

recycled aggregate content in the concrete mixes, the lower the workability (slump) of the concrete due to high water absorption of the recycled aggregate. A detrimental effect on concrete workability was reported by Hurley and Bush (2007) from the investigation of the impact of additional water demand by recycled coarse aggregate. This occurred as the percentage substitution of virgin coarse aggregate by recycled aggregate increased.

Akbari et al. (2011) researched the effect of recycled aggregate on properties of recycled aggregate concrete compared with natural aggregate concrete. The results revealed that workability reduced with higher content of recycled aggregate. Adnan et al. (2011), investigated the use of recycled aggregate as replacement for coarse aggregate in concrete mixes. The results showed reduction in slump due to high water absorption associated with recycled aggregate. Similar findings were reported by Peng et al. (2003) and Sivakumar et al. (2014). However, the workability was improved with the incorporation of 10 - 20% fly ash.

Ravindrarajah et al. (1987), assessed fresh properties of recycled aggregate concrete and reported no significant effect on workability of the concrete mix with the incorporation of coarse aggregate and /or fine aggregate. This observation agreed with the findings by Hansen and Narud (1983). Manzi et al. (2013), investigated the short and long-term behaviour of structural concrete with recycled concrete aggregate and reported a considerable reduction in workability of recycled aggregate concrete at 100% recycled aggregate content. Similar trend was reported by Lima et al. (2013) form the investigation of the physical properties and mechanical behaviour of concrete incorporating recycled aggregates and fly ash.

2.2.2.2 Effect of fibre

Ramakrishnan et al. (1989b) conducted research on flexural behaviour and toughness of fibre reinforced concrete and concluded that, the workability at higher dosage of fibre (i.e. 2.0%) by volume of concrete yielded the least workability. This was attributed to entrapped air in the concrete mix. A satisfactory result was later achieved with the incorporation of adequate measure of high-range water reducer (Superplasticiser). Hassan et al. (2011) agreed that high concentration of synthetic macro fibres causes reduction in slump and thus recommend the use of superplasticiser for adequate adjustment of workability. The use of fibres in controlling cracks in concrete was studied by Balik (2011). The result identified the reduction in workability of the concrete with higher dosage of synthetic macro fibres. This effect was attributed to large surface area of the fibre which consumes some fractional amount of the mortar. Tattersall and Banfill (1983), investigated the rheology of fresh concrete incorporating fibre and reported a considerable reduction in workability caused by interconnection of fibres and twisting around the aggregate particles.

2.2.2.3 Effect of microsilica

Mazloom et al. (2004) investigated the effect of silica fume on mechanical properties of high-strength concrete. Results indicate reduction in workability of concrete with increasing microsilica content. Tijani et al. (2015a) conducted research on how to enhance the performance of recycled aggregate concrete using microsilica and reported reduction in concrete incorporating microsilica due to the large surface area of the microsilica particles. Similarly, Deshini (2007) reported that the incorporation of micro silica as an admixture in concrete reduced the workability of the fresh concrete.

However these reductions in fresh concrete workability were mitigated by the addition of superplasticiser in order to meet the specified requirements. These findings corroborated with the results reported by Rao.Hunchate et al. (2014)

2.3 Mechanical Properties of Hardened Concrete

2.3.1 Compressive Strength

2.3.1.1 Effect of recycled coarse aggregate

Poon et al. (2007) investigated the effect of recycled aggregate on workability and bleeding of fresh concrete. Results suggested that compressive strength reduces with increasing recycled aggregate content in the mix. A reduction of about 24% at 100% recycled aggregate content with reference to control concrete was reported. Sivakumar et al. (2014), reported a reduction in compressive strength as the substitution of natural coarse aggregate by recycled coarse aggregate increases. However, an increase in strength was recorded with a little reduction in water/cement ratio. Also by reducing the water cement ratio and incorporating admixture, a target compressive strength of 40MPa was achieved with about 30-40% recycled coarse aggregate content in the concrete mix.

Rahal (2007) investigated the difference between the mechanical properties of recycled coarse aggregate concrete and natural aggregate concrete. The results shows that the average cube and cylinder compressive strength of recycled aggregate concrete were 88.4% and 92.2% respectively of the normal aggregate concrete. This implied about 10% reduction in compressive strength occurred in recycled aggregate concrete and this result was corroborated by Ravindrarajah et al. (2000).

Katz (2003) investigated the properties of concrete incorporating recycled aggregate recovered from partially hydrated old concrete. The results revealed that, the use of recycled aggregate led to reduction in the compressive strength of the concrete due to lower strength compared to strength of the virgin aggregate. Yamato et al. (1998) reported compressive strength reductions of about 20%, 30% & 45% respectively in concrete mixes corresponding to 30%, 50%, and 100% recycled aggregate content respectively in the mix.

Peng et al. (2003) conducted an experiment on the impact of recycled coarse aggregate strength upon the workability and strength of recycled aggregate concrete. The result indicated that recycled aggregate concrete produced less compressive strength than natural aggregate concrete. However, with the incorporation of about 10 - 20% fly ash, the compressive strength of recycled aggregate concrete increased more than the corresponding conventional concrete at 28-day curing age and beyond.

Parekh and Modhera (2011), assessed the use of recycled aggregate concrete and reported a strength loss of about 40% with increasing content of recycled aggregate in the concrete mix, whereas no loses was recorded below 30% substitution of natural aggregate by recycled aggregate. Similar reduction in compressive strength as recycled aggregare content increases was reported by Kumutha and Vijai (2010). At 100% recycled aggregate content, about 28% reduction in compressive strength with reference to the control concrete mix was observed. Yang et al. (2010) corroborate these findings. Schoppe (2011) findings on shrinkage and modulus of elasticity in recycled aggregate concrete indicated reduction in compressive strength of recycled coarse aggregate concrete (saturated & dried samples) with increasing content of recycled coarse aggregate in the concrete mix and water-cement ratio respectively.

However, contrary to the findings by previous researchers, higher compressive strength was reported at 100% recycled coarse aggregate content while lower results was recorded at 50% content. The lower result at 50% recycled aggregate content was attributed to heterogeneity resulting from variation in physical characteristics between 50% natural & recycled coarse aggregates respectively, while at 100% recycled aggregate content, an apparent homogenous development & improved bonding of the recycled coarse aggregate occurred (Schoppe, 2011).

Many researchers (Mandal et al. (2002); Limbachiya (2003); Estefano de Oliveira et al. (2008); Akbari et al. (2011); Abd Elhakam et al. (2012); Thomas et al. (2013); Vyas and Bhatt (2013); and Sivakumar et al. (2014)), agreed that below 30% replacement of natural coarse aggregate by recycled aggregate in the concrete mix, no significant reduction in compressive strength was observed whereas above this limit the strength decreases.

2.3.1.2 Effect of fibre

Ahmad et al. (1988) measured the properties of fibre reinforced concrete and reported that the effect of fibres on compressive strength of concrete was insignificant. Zollo (1984), investigated the use of collated fibrillated polypropylene fibers (CFP) at low fiber volumes in fibre reinforced concrete. The result indicated that the incorporation of 0-3% polypropylene fibres to concrete mix produced a negative impact on the compressive strength and the strength decreases with higher dosage of fibres. This outcome was corroborated by the findings by Hughes and Fattuhi (1976).

Several researchers (Guirguis and Potter (1985); Malisch (1986); Ramakrishnan et al. (1987); Nagabhushanam et al. (1989); Ramakrishnan et al. (1989b); Vondran et al. (1989)) reported no significant effect of fibre on compressive strength of concrete with increasing dosage of fibres from 0.1-2%. Although slight variations were identified from their reports which could be attributed to experimental errors and different source of concrete materials. On a contrary, Mindess and Vondran (1988) investigation on properties of concrete reinforced with fibrillated polypropylene fibres under impact loading recorded about 25% increase in compressive strength with the incorporation of 0.5% polypropylene fibres

2.3.1.3 Effect of Microsilica

Verma et al. (2012) studied the impact of micro silica on the strength of Ordinary Portland Cement concrete. The result showed about 25% increase in compressive strength with incorporation of microsilica. This increase was attributed to the reaction between the fine particles of microsilica and the lime content in cement which led to reduction in voids in the concrete. The replacement of cement by 15% microsilica in the concrete mix effectively increased the compressive strength while higher replacement reduced the trend (Rao.Hunchate et al., 2014).

Annadurai and Ravichandran (2014) developed a mix design for high strength concrete incorporating admixtures. Results suggests compressive strength increase betwwen 50 –

70Mpa at 15% substitution of cement by microsilica. Tijani et al. (2015a) also identified significant increase in compressive strength of concrete incorpating 5% microsilica and attributed this result to the densifying properties and pozzolanic action of microsilica which had smaller particle size than cement particles. The incorporation of micro silica increases the compressive strength of concrete due to the development of strong matrix arising from the combination of both pozzolanic and micro-filler effect attributes of microsilica (Malhotra and Mehta, 1996).

2.3.2 Tensile Splitting Strength

2.3.2.1 Effect of recycled coarse aggregate

Rao et al. (2011) investigated the behaviour of recycled aggregate concrete under drop weight impact load. The results revealed reduction in indirect tensile strength with increasing percentage of recycled aggregate. Akbari et al. (2011), studied the impact of recycled aggregate on behaviour of normal strength concrete. The findings showed about 26% reduction in tensile splitting strength with higher substitution of natural aggregate by recycled aggregate. These findings were corroborated by Li (2008), and Xiao and Lan (2006).

Kumutha and Vijai (2008), investigated the effect of recycled coarse aggregates on properties of concrete and discovered that the tensile splitting strength decreases gradually as recycled coarse aggregate content in the concrete mix increases. About 36% reduction in tensile strength was recorded at 100% recycled aggregate content while Serifou et al. (2013) recorded about 18% reduction . Similar trend of reduction in tensile strength with increasing amount of recycled coarse aggregate were also reported by Xiao and Lan (2006); Li (2008); Lima et al. (2013); Sivakumar et al. (2014).

Abd Elhakam et al. (2012), researched the properties of recycled aggregate concrete and mentioned that the tensile strength decreases as percentage content of recycled coarse aggregate increases. Thomas et al. (2013) studied the physical and engineering durability properties of recycled aggregate concrete and reported that at 20%, 50%, and 100% recycled aggregate content in the concrete mix, the corresponding tensile strength were 90%, 85%, and 80% respectively of the control concrete mix. Most of these findings attributed the reduction in tensile splitting strength to the porous structure of the recycled aggregate.

2.3.2.2 Effect of Fibre

Bagherzadeh et al. (2012a) investigated the impact of incorporating polypropylene fibres in reinforced lightweight cement composites. The results indicated higher tensile strength in concrete mix incorporated with fibre as the dosage increases compared with the control concrete mix without any fibre dosage. Farjadmand and Safi (2012) reported about 35% increase in tensile strength as the dosage of synthetic macro fibre in concrete mix increased compared to control plain concrete. Hassan et al. (2011) conducted a research on mechanical behaviour of synthetic macro fibre reinforced concrete and reported an increase in indirect tensile strength of about 15% with reference to the control concrete. However, higher fibre dosage produced a slight reduction of about 1% due to poor workability resulting from higher volume of fibres.

2.3.2.3 Effect of Microsilica

Bhanja and Sengupta (2005) investigated the influence of silica fume on the tensile strength of concrete and discovered that, the strength increases as substitution of cement by microsilica increases up till 15% replacement beyond which the result becomes less significant. Baid and Bhole (2013) researched the effect of microsilica on mechanical properties of concrete and reported that, the incorporation of microsilica slightly increases the tensile splitting strength to about 17% with about 9% microsilica content.

2.3.3 Flexural Strength

2.3.3.1 Effect of recycled coarse aggregate

Akbari et al. (2011) investigated the effect of recycled aggregate on behaviour of normal strength concrete and reported about 23% reduction in flexural strength with increasing recycled aggregate content. Kumutha and Vijai (2008), conducted a research on the impact of recycled coarse aggregates on properties of concrete and identified gradual reduction in strength as the percentage substitution of natural aggregate by recycled coarse aggregate increases. A reduction of about 50% in strength was reported at 100% recycled aggregate content. Similar gradual reduction trend was reported by Serifou et al. (2013) and about 18% reduction in flexural strength was recorded at 100% recycled coarse aggregate content.

2.3.3.2 Effect of Fibre

The increase in fibre dosage in the concrete mix enhances the flexural strength performance of concrete incorporating fibres compared with the control concrete without fibre. The reason being the positive contribution of higher dosage of fibres to tensile load before failure of the specimen occurred (Bagherzadeh et al., 2012a). Altoubat et al. (2006) researched the effect of synthetic fibres on structural behaviour of concrete slabs-on-ground and found that the incorporation of structural synthetic fibres in the concrete mix increased the flexural strength even at a very low dosage and at about 0.32 – 0.48% addition, an increase of between 25-54% in flexural strength was recorded, thus corroborating the findings that the flexural strength increases as dosage of synthetic fibre increases. However, only a slight increase in flexural strength was reported by Zollo (1984) at 0.1% dosage of collated fibrillated polypropylene fibres in FRC. Beyond this dosage precisely 0.2 - 0.3%, a slight reduction in flexural strength was recorded.

Jiabiao et al. (2004) reported that the resistance of fibre reinforced concrete after the first crack appeared to a ratio of maximum load under bending increased with more dosage of synthetic macro fibre. This efficiency in delay of micro cracks growth is a function of the increasing dosage rate of fibre (James et al., 2002). Contrary to the above views, Alhozaimy et al. (1996) reported from the study of mechanical properties of polypropylene fibre reinforced concrete that polypropylene fibre dosage in the concrete mix has no significant effect on the flexural strength of concrete incorporated with 0.05% - 0.30% volume fraction of fibres. However, there was no general consensus views among many published literatures with respect to the impact of polypropylene fibres on concrete.

2.3.3.3 Effect of Microsilica

Baid and Bhole (2013) studied the effect of microsilica on mechanical properties of concrete and reported that, the inclusion of microsilica as a replacement of cement shows slight increase in 28 days flexural strength. About 27% increase in flexural strength which represent maximum increase in characteristic strength was recorded at 15% microsilica content. The addition of microsilica to concrete mix significantly enhanced the flexural strength with reference to the control mix and this was attributed to the ability of microsilica to improve the microstructure of the interfacial transition zone (Pauw and Lauritzen, 1994). Bhanja and Sengupta (2005) also reckoned that the flexural strength increased significantly with higher substitution of cement with micro silica while the optimal results occurred at 15% microsilica replacement for cement.

2.3.4 Static Modulus of Elasticity

2.3.4.1 Effect of recycled coarse aggregate

Rao et al. (2011) investigated the behaviour of recycled aggregate concrete under drop weight impact load and found that the modulus of elasticity decreases with increase in recycled coarse aggregate content in the concrete mix. Many researchers (Hansen (1992), Nojiri (1994), Ahmad et al. (1996), Merlet and Pimienta (1993), Topçu and Günçan (1995), Sivakumar et al. (2014)) studied high strength concrete using recycled coarse aggregate and reported reduction in modulus of elasticity with increasing replacement of natural aggregate by recycled coarse aggregate.

Frondistou-Yannas (1977) researched the use of waste concrete as aggregate for new concrete and discovered that the static elastic modulus of recycled coarse aggregate concrete was about 60 - 100% of the virgin coarse aggregate concrete due to lower modulus of elasticitiy associated with recycled coarse aggregate compared to natural aggregate. This corroborates the findings by Ong and Ravindrarajah Sri (1987) that the static elastic modulus of recycled coarse aggregate was about 60% less than the results obtained with conventional concrete when both recycled and fine aggregate are used. Xiao et al. (2005a) investigated the mechanical characteristics of recycled aggregate under uniaxial loading and discovered that the elastic modulus reduces as the percentage content of recycled aggregate increases. About 45% reduction was recorded at 100% recycled coarse aggregate content. Gerardu and Hendriks (1985), reported about 15% reduction in modulus of elasticity of recycled aggregate concrete while about 40% reduction at a relatively high water-cement ratio of 0.75 was reported by Frondistou-Yannas (1977) without any significance at a lower water-cement ratio of 0.55.

Hansen and Boegh (1985a) investigated the elasticity and drying shrinkage of recycled aggregate concrete and found that both static and dynamic modulus of elasticity of recycled aggregate concrete were between 15 to 30% less than the corresponding moduli of the parent concrete. Ravindrarajah et al. (1987), also reported about 14% reduction in static elastic modulus of recycled aggregate concrete compared with virgin coarse aggregate concrete. However, Estefano de Oliveira et al. (2008) revealed that, the modulus of elasticity of concrete produced from recycled aggregate remain relatively similar to normal concrete, when the percentage content of the recycled coarse aggregate is below 40%. Above this optimum 40% the modulus of elasticity decline faster due to the rate of water absorption of recycled aggregate.

In a study by Eguchi et al. (2007) on the use of recycled aggregate as mixture in concrete construction, a decreasing trend in modulus of elasticity occured as the recycled aggregate concent increased. Schoppe (2011) investigated the shrinkage and elastic modulus of concrete incorporating recycled aggregate, and concluded that the modulus of elasticity of recycled concrete reduced between 0 – 20%, when compared to the reference concrete. The elastic modulus of recycled aggregate concrete was about 55–100% of that of conventional aggregate concrete (Frondistou-Yannas, 1977; Nixon, 1978; Hansen and Boegh, 1985b; Hansen, 1986; Katz, 2003; Xiao et al., 2005a; Rakshvir and Barai, 2006; Domingo-Cabo et al., 2009; and Rao et al., 2011b). This result was due to the lower modulus of elasticity of recycled coarse aggregate (Frondistou-Yannas, 1977; Xiao et al., 2005a; and Rao et al., 2011b).

Generally, the modulus of elasticity reduces with more recycled coarse aggregate content in the concrete mix. However, Limbachiya et al. (2000) reported a contrary observation from findings by some researchers (Frondistou-Yannas, 1977; Hansen and Boegh, 1985b; and Ong and Ravindrarajah Sri, 1987) that the elastic modulus of natural aggregate concrete and high strength recycled coarse aggregate concrete are very similar.

2.3.4.2 Effect of Fibre

Hassan et al. (2011) investigated the mechanical behaviour of synthetic macro fibre reinforced concrete and discovered a significant impact due to fibre addition with the relationship between stress and strain of fibre reinforced concrete. It was observed that the strain values of the fibre reinforced concrete increased by about 50-60% with increasing amount of synthetic macro fibres between 0.33-0.51% respectively. The modulus of elasticity of the concrete decreased due to inverse relationship between the modulus of elasticity and strain since no positive impact was observed on the ultimate stress. This findings corroborate the observations reported by Schoppe (2011) and Farjadmand and Safi (2012) that there is a decreasing trend in modulus of elasticity as the recycled coarse aggregate content increases in concrete mix. The incorporation of microsilica reduces porosity of the interfacial transition zone between cement paste and the aggregate, thus enabling the stiffness of the aggregate to contribute more to the general stiffness of the concrete (Helland et al., 1988).

2.3.4.3 Effect of Microsilica

Xiao et al. (2005b) conducted research on mechanical properties of recycled aggregate concrete under uniaxial loading. Result showed higher elastic moduli with concrete incorporating 15% replacement of cement by microsilica. This findings was corroborated by Burg and Ost, 1992; Xiao et al. (2005b); and Seitl et al., 2010.

2.3.5 Permeability

2.3.5.1 Effect of recycled coarse aggregate

Deterioration in reinforced concrete is majorly caused by corrosion of the steel reinforcing bars which are prone to corrosion due to the presence of aggressive liquids and/or gases in the concrete through permeation. This eventually affects the concrete durability as the permeability increases. Wainwright et al. (1993) investigated the performance of concrete incorporated with fine and coarse recycled concrete aggregate. Result indicate higher porosity and permeability when coarse recycled aggregate replaced natural aggregates and more significant result was recorded with the replacement of natural fines by recycled fines.

Gómez Soberón et al. (2001) investigated the effect of recycled concrete aggregate on the permeability of concrete and found that permeability increases considerably with more recycled concrete aggregate content compared to control concrete due to the porous nature of recycled concrete aggregate. In the study conducted by Wainwright et al. (1993), it was reported that the permeability of recycled concrete was twice that of conventional concrete. Hansen and Boegh (1985b) also studied the elasticity and drying shrinkage of recycled concrete aggregate and explained that the permeability increases up to 2 – 5 times the value for control concrete mix. This finding was attributed to high porosity associated with recycled concrete aggregate

2.3.5.2 Effect of fibre

Singh and Singhal (2011) assessed the influence of fibre parameters on the permeability of steel fibre reinforced concrete and reported significant reduction in permeability as the steel fibre dosage increases. No significant impact was reported on the coefficient of water permeability.

2.3.5.3 Effect of Microsilica

The inclusion of mineral admixtures or supplementary cementitious materials in concrete reduces the permeability and thus protect the concrete from aggressive chemicals by providing resistance against deterioration. The incorporation of microsilica in concrete exposed to aggressive environment produce low permeability due to its high pozzolanic character and extreme finess. Khan and Lynsdale (2002) investigated the strength, permeability and carbonation of high-performance concrete. The results showed that the optimum permeability and strength were achieved with the incorporation of 8-12% microsilica as replacement for the ordinary Portland cement. Addition of microsilica significantly reduced permeability as the microsilica content increases due to its densifying effect on microstructure which eventually result into reduction in porosity and subsequently produced denser concrete (Tijani et al., 2015a).

2.3.6 Flexural Fatigue Assessment

2.3.6.1 Effect of recycled coarse aggregate

Fatigue is a process of progressive and permanent material damage under repeated (cyclic) loading. The failure takes place under repetitive or cyclic load influence. The peak values are considerably smaller than safe loads estimated on the basis of static load test (Ong and Ravindrarajah Sri, 1987). Xiao et al. (2013) investigated the fatigue behavior of recycled aggregate concrete under compression and bending cyclic loadings. Results showed reduction in the fatigue life behaviour of recycled aggregate concrete at 100% recycled coarse aggregate content under cyclic bending loading for similar stress level. Ong and Ravindrarajah Sri (1987) studied mechanical properties and fracture energy of recycled aggregate concretes and reported reduction in the no of cycles (fatigue life) of recycled aggregate concrete as the percentage substitution of natural aggregate by recycled aggregate increases at all stress levels.

Thomas et al. (2014a) investigated the fatigue limit of recycled aggregate concrete and reported more loss of stiffnes in recycled aggregate concrete than in the reference (natural aggregate) concrete. No significant difference in fatigue life of concrete was reported by y Certificación (2009) as recycled coarse aggregate increased from 50% to 100%. However, there was reduction in the fatigue life of recycled coarse aggregate concrete when compared with natural aggregate concrete. Different results were however observed by Xiao et al. (2013) under uniaxial compression fatigue test. Results indicate that recycled aggregate concrete has more fatigue life than natural aggregate concrete at 100% recycled coarse aggregate content.

2.3.6.2 Effect of fibre

Thomas et al. (2014b) evaluated the fatigue behaviour of recycled aggregate concrete incorporated with steel fibre. Result indicate that the fatigue life of recycled aggregate concrete increased as the substitution of natural aggregate by recycled aggregate increased in comparison with the control concrete. Reduction in fatigue stress as the stress level increases was also reported. The study conducted by Schoppe (2011) on shrinkage and modulus of elasticity in concrete with recycled aggregates showed that the incorporation of steel fibres have positive impact on the fatigue performance of concrete under flexural fatigue loading. This result was attributed to the fibres ability to bridge cracks and subsequently prolong the fatigue life. However, Schoppe (2011) reported no significant impact on the fatigue life of concrete incorporating steel fibres under compressive fatigue loading due to differences in failure pattern between compressive and flexural loading respectively.

Most researchers agree that, fibre reinforced concrete posses better fatigue behaviour than plain concrete. Domingo-Cabo et al. (2009) explained that the efficiency of fibres in improving the fatigue life of concrete is a function of fibre distribution which could have detrimental impact on the fatigue life of concrete. Fibres also tend to dissipate less energy at higher stress levels than at lower stress levels (Rakshvir and Barai, 2006). Singh and Singhal (2011) investigated the influence of fibre parameters on the permeability of steel fibre reinforced concrete. Report showed that the incorporation of fibres in the concrete could have detrimental effect on the fatigue life of concrete unless the fibres are adequately and evenly distributed in the concrete mix.

2.4 Summary of Existing development

There is consensus among researchers with respect to low workability of recycled aggregate concrete with increasing amount of recycled coarse aggregate, fibre dosages, and mineral admixture (Microsilica) in the concrete mix. However, there are contrary reports on the impact of fibre, microsilica and higher content of recycled aggregate in concrete incorporating fibre and microsilica. Some researchers held that compressive strength, tensile splitting strength, flexural strength, and elastic modulus reduces as the aforementioned materials increases in concrete mix while other researchers reported increase in mechanical properties and insignificant effect respectively.

The majority of researchers reported increasing permeability with increasing recycled coarse aggregate content and decreasing permeability with inclusion of fibre and microsilica. A general consensus on the effect of increasing the content of recycled coarse aggregate on the fatigue life of recycled coarse aggregate concrete was that the fatigue life reduces whereas opinions differ on the effect of fibre and microsilica. While some researchers reported positive impact with increase in fatigue life, others suggested an insignificant impact. The difference in views could be linked to different sources of materials, experimental errors, and methods employed by individual researchers.

2.5 Knowledge gap

From several research findings reviewed under this chapter, the influence of the combination of microsilica, synthetic macro fibre, and recycled aggregate concrete is yet to be investigated. The contributions of microsilica as an addition to cement in concrete has not been widely investigated as only few researchers had studied the benefits of using microsilica in recycled aggregate concrete as a percentage addition rather than replacement but at a higher water-cement ratio. However, the majority of the researchers, conducted research on recycled aggregate concrete without incorporating microsilica. This research work aims to investigate the effect of incorporating microsilica as a percentage addition to recycled coarse aggregate concrete rather than as partial replacement for cement.

Most researchers in a similar way to the British Standard (BS8500-2, 2006) suggests the use of about 30% recycled coarse aggregate as a replacement for conventional coarse aggregate in concrete because findings have shown that there is no significant effect at such percentage replacement. However, it is one of the objectives of this research work to assess the potential of raising this recommended percentage utilization of recycled coarse aggregate in concrete mix beyond 30%. This research work would leverage on the properties of synthetic macro fibre and micro silica and synergise these properties in order to achieve the set target thereby reducing the consumption of natural coarse aggregate which is about 60-75% in concrete mix.

3 RESEARCH METHODOLOGY

The methodology employed in order to achieve the set objectives is described under this chapter.

3.1 Experimental Work

The experimental work is at the core of the research work. In order to evaluate the physical and mechanical characteristics of the concrete produced from the aforementioned materials under theoretical work, some laboratory work is required. The percentage of natural coarse aggregate replacement by recycled coarse aggregate was chosen as 0%, 25%, 50%, 75%, and 100% by weight of coarse aggregate respectively with 0% taken as the control or reference concrete. 54mm forta-ferro synthetic macro fibre was also incorporated at different dosages of 0%, 0.11%, and 0.5% for different batches of concrete.

Laboratory testing was also performed on fresh and hardened concrete samples in order to determine their workability, compressive strength, tensile splitting strength, flexural strength, modulus of elasticity, water permeability (Autoclam), and fatigue performance respectively in accordance to British Standards and Eurocodes. The impact of recycled coarse aggregate, synthetic macro fibre, and microsilica on the properties of concrete were also investigated from the results of tests carried out which enabled comparison to be made with control experiment. The fatigue performance obtained from the combined use of these materials under investigation would be assessed under cyclic loadings.

3.1.1 Concrete materials

The essential concrete materials used in the experimental work are shown in Table 1 below.

Table 1: Concrete materials

Materials	**Description**
Cement	CEM II/B-V 32,5N (Portland – pulverised fly ash cement)
Synthetic macro fibre	54mm Forta- Ferro. Virgin copolymer / polypropylene, Specific gravity of 0.91, and tensile strength from 570-660 MPa. Non-corrosive, non-magnetic and are 100% alkali resistance.
Microsilica	Elkem Microsilica Grade 940-U
Natural coarse aggregate	Crushed gravel with nominal maximum size of 10mm.
Recycled coarse aggregate	Maximum size of 10mm supplied by Coleman and company, Birmingham, UK
Natural fine aggregate	River sand with maximum particle size of 5mm.
Superplasticiser (Alphaflow 420)	Modified synthetic Carboxylated polymer

3.1.1.1 Cement

The cement used in this research was Portland-pulverised fly ash cement shown in Figure 1 which has design strength of 32,5N/mm² (CEM II/B-V 32,5N) and also conforms to BS EN 197-1:2011. The Pulverished Fly Ash (PFA) incorporated was approximately 30%, and this was considered during the concrete mix design. These cement were stored within the laboratory, numbered with dates and used according to date of delivery.

Figure 1: Portland-pulverised fly ash Cement [CEM II/B-V 32,5N]

3.1.1.2 Microsilica

The Grade 940-U microsilica used in the laboratory as shown in figure 7 was obtained from Elkem microsilica company.

Figure 2: Grade 940-U Microsilica Supplied by Elkem

Typical properties of Grade 940-U microsilica is given in Table 2.

Table 2: Typical properties of Grade 940-U microsilica (Courtesy:Elkem mocrosilica)

Form:	Ultrafine amorphous powder (respirable dust). Dust forms agglomerates.
Colour:	Grey, off-white
Odour	Odourless
Melting Point (°C)	1550-1570
Solubility (Water):	Insoluble/Slightly soluble
Solubility (Organic solvents):	Insoluble/Slightly soluble
Specific Gravity (water=1)	2.2-2.3
Bulk density (U) (kg/m3)	200-350
Specific surface (m^2/g):	15-30
Particle size, mean (µm):	~ 0.15 (< 0.1 % of primary particles > 45 µm)
Silicon (SiO_2)	Minimum 90%
Loss of Ignition	Maximum 3%
Coarse particle >45 µm	Maximum 1.5%

There are 2 distinct ways in which microsilica enhances concrete strength and durability These are;

1. By acting as a filler to reduce the average size of pores present in cement paste and;
2. By providing more even distribution and higher volume of hydration products while acting as a pozzolan.

3.1.1.3 Natural Coarse Aggregate (Crushed gravel)

Crushed gravel with nominal maximum size of 10mm and relative density of 2.7 was used as natural coarse aggregate in the research work. The materials were stored outside the laboratory at a designated area. The water absorption and particle density were evaluated as 1.44% and 2505kg/m³ respectively at saturated surface dry (SSD) condition. Figure 8 shows the sample of the crushed gravel used for concrete work in the laboratory.

Figure 3: Natural coarse aggregate (Crushed gravel with maximum size 10mm)

3.1.1.4 Natural Fine Aggregates (Sand)

River sand with water absorption and relative density of 1.67% and 2245kg/m³ respectively at saturated surface dry (SSD) condition were used as natural fine aggregate in the research. Figure 9 shows the river sand sample used for concrete work and was stored outside the laboratory.

Figure 4: Natural fine aggregate (River sand)

3.1.1.5 Recycled Coarse Aggregates

Recycled aggregates are mainly crushed concrete and brick masonry obtained from materials that were previously used in construction activities and recovered from demolition debris (Nelson, 2004). They may be grouped as either recycled concrete aggregate (RCA) when the components are largely from crushed concrete or generally referred to as recycled aggregates (RA) when they are made up of substantial amounts other than crushed concrete. The major difference between recycled coarse aggregate and natural coarse aggregate is that the former consists of two separate materials; natural aggregate and attached or adhered cement mortar. BRE (1998), classified recycled aggregates into three types. These are; RCA [I], RCA [II], RCA [III] as indicated in Table 3.

Table 3: Classification of recycled aggregates (BRE (1998)

Class	Origin (normal circumstances)	Brick content by weight
RCA(I)	Brickwork	0-100%
RCA(II)	Concrete	0-10%
RCA(III)	Concrete and brick	0-50%

The recycled coarse aggregate used for the research has a nominal maximum single-size of 10mm and was obtained from Coleman & company recycling plant in Birmingham. The water absorption and particle density were evaluated as 7.65% and 2323kg/m³ respectively at saturated surface dry (SSD) condition. Figure 10 shows the sample of recycled coarse aggregate used for concrete work in the laboratory.

Figure 5: Recycled coarse aggregate (Supplied by Coleman & co. maximum size 10mm)

There were about 5.2% impurities (see figure 25 and table 17) in the recycled coarse aggregate used for the experimental work. However, these impurities were not removed in order to use the recycled aggregate in its original packaged state and also to identify any effect on the concrete produced.

3.1.1.6 Synthetic Macro Fibre

Synthetic macro fibre is a flexible, macroscopically homogenous body, with a high aspect ratio and a small cross-section (Zheng and Feldman, 1995). Macro fibres are very efficient and effective in enhancing various materials properties which includes; flexural toughness, impact resistance, and resistance to fatigue respectively. They provide concrete with early tensile strength to a very good extent required for prevention and control of crack initiation. Figure 11 shows the sample of synthetic macro fibre incorporated in the concrete mix.

Figure 6: 54mm Forta-Ferro synthetic macro fibre

Macro fibre also provides internal support to concrete through restraints against the formation of plastic shrinkage. Since shrinkage of concrete is not preventable, macro fibre function as the crack control against drying shrinkage by intersecting cracks formed in the concrete, and this subsequently distribute the shrinkage stresses evenly thereby minimising the problems associated with cracks.

The synthetic macro fibre implored was produced by Forta-Ferro Inc. from 100% virgin copolymer/polypropylene material with a nominal length of 54mm and an aspect ratio of 79.5. It is a twisted bundle monofilament/fibrillated form fibre system grey in colour with specific gravity of 0.91, tensile strength between 570-660MPa, and conforms to A.S.T.M. C-1116.. The major benefit of the twisting nature of the fibre was to ensure thorough and even mix of the fibre throughout the concrete matrix. The synthetic macro fibre also prevent brittle failure caused by high load impact through energy absorption mechanism without breakage based on its design to retain its cross sectional shape.

3.1.1.7 Water

The reaction between the mixture of water and cement results in hardening of concrete through the process known as hydration. In order to prevent any deleterious substance from interfering with the process of hydration, water for concreting is recommended to be from a potable source. This is because the role of water in water to cement ratio is the most critical factor in concrete. Excess water reduces the strength of concrete while inadequate water make concrete less workable. Due to desire to ensure concrete workability and of required strength, it is necessary to balance the water to cement ratio in concrete mix. In view of this, potable drinking water from the laboratory was used for concrete mixing in order to enhance hydration of cement and mineral admixture, and enable proper binding effect. The source of water is free from any form of contamination otherwise, it would affect the physical and mechanical characteristics of concrete.

3.1.1.8 Superplasticizer

Superplasticizer is an extra-effective water-reducing admixture with a very great plasticizing effect on concrete (BCA, 1991). Superplasticiser permits a reduction in the water content of a concrete mix without affecting its consistency. It is widely used to increase the fluidity of concrete to give a mix with higher workability thereby leading to easier placing and compaction. Oscrete Alphaflow 420 shown in figure 12 was used as chemical admixture for the concrete.

Figure 7: Alphaflow 420 Superplasticizer (Supplied by Oscrete)

The advantage of the plasticising effect can be explored in reducing of free-water/cement ratio of the mix and increasing strength while maintaining the same workability. Superplasticizer also improves durability, quality, consistency of concrete and savings in cost in terms of economical mix design, and speeding the process of construction (J P Ridal et al., 2000). Oscrete Alphaflow 420 shown in figure 12 was used as chemical admixture for the concrete. It is a "new generation High Range Superplasticiser based on a modified synthetic carboxylated polymer" as mentioned by the manufacturer Oscrete Construction. Oscrete Alphaflow 420 was incorporated into concrete mixes in order to maintain same level of consistency between 60-180mm throughout the laboratory work as recommended from the concrete mix design calculations. The properties of Oscrete Alphaflow 420 are given in Table 4.

Table 4: Properties of Alphaflow 420 Superplasticiser (Oscrete Construction Products)

Nature	**Liquid**
Colour	Amber
Specific Gravity	1.06g/cm^3
pH	6.5
Chloride Content	<0.10%
Na_2O equivalent	<1.00%

3.1.1.9 Concrete Moulds

The dimension and types of concrete moulds used in the laboratory work are indicated in Table 5 and Figure 13 respectively.

Table 5: Concrete moulds conforming to BS EN 12390-1.

Mould type	Dimension (mm)	Volume (m³)
Cube	100x100x100	0.009
Prism	100x100x500	0.018
Cylinder	100Øx200	0.045

Figure 8: A Concrete moulds conforming to (BS-EN-12390-1, 2012)

3.2 Concrete mix design and sequence

This is an important stage in concrete production since it includes the determination of the relative quantities of the materials that constitute concrete with the object of producing an economical concrete as possible which satisfy certain minimum properties or characteristics such as strength, durability and required consistency.

3.2.1 Concrete mix design considerations

The Building Research Establishment (BRE) guidelines for design of normal concrete mixes were employed. With due consideration of the requirements of the BRE guidelines, it became imperative to make some necessary adjustments in order to comply with the criteria required for the use of the guidelines and thus select the appropriate quantity of materials required. The Building Research Establishment (BRE) guidelines used the saturated surface dry (SSD) condition for normal concrete mixes which in practice does not represent the natural true state of the aggregates used in the course of the laboratory work. Therefore it became very important to check the rate of water absorption of each aggregate in order to compensate for it during addition of the free water while mixing. The adjustments were conducted in compliance to (BS-EN-1097-6, 2013). Wire Basket method was employed to determine the particle density and water absorption rate of both natural coarse and recycled coarse aggregates while Pyknometer method was used for fine aggregate (sand).

The cement strength class given in table 2 of the Building Research Establishment (BRE) guidelines for the design of normal concrete mixes were 42.5 and 52.5 respectively whereas the actual cement strength class supplied by Rugby cement for the laboratory work was 32.5 (Portland-pulverised fly ash cement CEM II B/V 32,5N). Therefore, it was important to interpolate and work out the approximate compressive strength of this cement in order to obtain the required free-water/cement ratio.

3.2.1.1 Concrete mix design (Phase One)

Three Series of concrete mixes were designed in accordance to the conventional UK mix design method, that is, Building Research Establishment (BRE) design of normal concrete mix manual. Series 1 represents the control experiment without synthetic macro fibre addition. Series 2 consists of 0.5% (4.45kg/m^3) synthetic macro fibre dosage while Series 3 incorporates 0.11% (1kg/m^3) addition of synthetic macro fibre by volume of concrete respectively. The concrete mixes were designed for characteristics compressive cube strength of 50MPa at 28-day curing age, free-water/cement ratio (w/c) of 0.39, and high workability (60-180mm) as illustrated in Table 66. A total of four hundred and fifty (450) concrete samples were produced and investigated from three different mixes shown in Tables 6, 7, and 8 at saturated surface dried (SSD) state respectively. These consist of 9 standard cubes of 100x100x100mm, 12 cylinders of 100mm diameter and 200mm high, and 9 standard prisms of 100x100x500mm for each concrete batch per Series. The aim of the experiment was to assess the impact of inclusion of 54mm forta-ferro synthetic macro fibre on the physical and mechanical characteristics of recycled coarse aggregate concrete.

Table 6: Concrete mix details – Series 1 (0% F, 0% M)

Recycle Aggregate by weight of coarse aggregate. (%)	0	25	50	75	100
Cement (kg/m³)	583	583	583	583	583
Sand (kg/m³)	603	603	603	603	603
Gravel (kg/m³)	904	678	452	226	0
RCA. (kg/m³)	0	226	452	678	904
Free-water (kg/m³)	230	230	230	230	230

RCA --- Recycled Coarse Aggregate, F --- Fibre, M --- Microsilica

Table 7: Concrete mix details – Series 2 (0.5% F, 0% M)

Recycle Aggregate by weight of coarse aggregate. (%)	0	25	50	75	100
Cement (kg/m³)	583	583	583	583	583
Sand (kg/m³)	603	603	603	603	603
Gravel (kg/m³)	904	678	452	226	0
RCA. (kg/m³)	0	226	452	678	904
Free-water (kg/m³)	230	230	230	230	230
Synthetic Macro Fibre - 0.5% by volume of concrete (kg/m³)	4.5	4.5	4.5	4.5	4.5

RCA --- Recycled Coarse Aggregate, F --- Fibre, M --- Microsilica

Table 8: Concrete mix details – Series 3 (0.11% F, 0% M)

Recycle Aggregate by weight of coarse aggregate. (%)	0	25	50	75	100
Cement (kg/m³)	583	583	583	583	583
Sand (kg/m³)	603	603	603	603	603
Gravel (kg/m³)	904	678	452	226	0
RCA. (kg/m³)	0	226	452	678	904
Free-water (kg/m³)	230	230	230	230	230
Synthetic Macro Fibre - 0.11% by volume of concrete (kg/m³)	1	1	1	1	1

RCA --- Recycled Coarse Aggregate, F --- Fibre, M --- Microsilica

3.2.1.2 Concrete mix design (Phase Two)

Sequel to phase one experiment, phase two concrete mix design also followed the conventional UK mix design method (BRE, 1997), 'design of normal concrete mix manual'. It consists of five concrete mixes incorporating 5% microsilica as an addition to cement and 1kg/m³ synthetic macro fibre dosage as shown in Table 9. In order to maintain similar consistency level as specified in the design mix, a High Range Superplasticiser (Alphaflow 420) based on a modified synthetic carboxylated polymer was used as chemical admixture at varying dosage by volume of cement respectively. The object of phase two experiment was to compare the results obtained in phase two against the results recorded in phase one in order to assess the effect of microsilica on fibre reinforced concrete with partial and full substitution of natural coarse aggregate by recycled coarse aggregate.

Table 9: Concrete mix details – Series 4 (0.11% F, 5% M)

Recycle Aggregate by weight of coarse aggregate. (%)	0	25	50	75	100
Cement (kg/m³)	583	583	583	583	583
Sand (kg/m³)	603	603	603	603	603
Gravel (kg/m³)	904	678	452	226	0
RCA. (kg/m³)	0	226	452	678	904
Free-water (kg/m³)	230	230	230	230	230
Synthetic Macro Fibre - 0.11% by volume of concrete (kg/m³)	1	1	1	1	1
Microsilica (kg/m³) - 5% by weight of cement	29.2	29.2	29.2	29.2	29.2
Superplasticiser by weight of cement (kg/m³)	2.33	2.33	2.33	3.50	3.50

RCA ---- Recycled Coarse Aggregate, F --- Fibre, M --- Microsilica

The concrete characteristics cube strength, water-cement ratio, and workability remain the same as in design mix in phase 1. A total of one hundred and sixty five (165) concrete samples were investigated respectively and these consists of 12 standard cubes of 100x100x100mm, 12 cylinders of 100mm diameter and 200mm high, and 9 standard prisms of 100x100x500mm for each concrete batch in a Series 4.

3.2.1.3 Concrete mix design (Phase Three)

Sequel to phase two experiment, phase three investigated the optimised use of microsilica as an addition to cement in fibre reinforced recycled aggregate concrete produced from phase two. A total of nine hundred and sixty (960) concrete samples were produced and tested from four concrete mixes shown in Tables 10-13. The design mix was done in accordance to the conventional UK mix design method, (BRE, 1997) at saturated surface dried (SSD) state respectively. Each concrete batch consists of 12 standard cubes of 100x100x100mm, 12 standard cylinders of 100mm diameter by 200mm high, and 24 standard prisms of 100x100x500mm. Concrete mixes in Series 4-7 incorporates same dosage of synthetic macro fibre of 1kg/m³ by weight of concrete and various microsilica addition of 5%, 10%, 15% and 20% respectively.

A High Range Superplasticiser (Alphaflow 420) was used as chemical admixture at varying dosages in order to maintain the designed workability. The dosage used was not excessive in order to prevent weakening of the concrete cohesion. The characteristics cube strength, free-water/cement ratio (w/c) and specified slump remain the same as in phase 1.

Table 10: Concrete mix details – Series 4 (0% F, 5% M)

Recycle Aggregate by weight of coarse aggregate. (%)	0	25	50	75	100
Cement (kg/m³)	583	583	583	583	583
Sand (kg/m³)	603	603	603	603	603
Gravel (kg/m³)	904	678	452	226	0
RCA. (kg/m³)	0	226	452	678	904
Free-water (kg/m³)	230	230	230	230	230
Synthetic Macro Fibre - 0.11% by volume of concrete (kg/m³)	1	1	1	1	1
Microsilica - 5% by weight of cement (kg/m³)	29.2	29.2	29.2	29.2	29.2
Superplasticiser by weight of cement (kg/m³)	2.33	2.33	2.33	3.5	3.5

RCA ---- Recycled Coarse Aggregate, F --- Fibre, M --- Microsilica

Table 11: Concrete mix details – Series 5 (0% F, 10% M)

Recycle Aggregate by weight of coarse aggregate. (%)	0	25	50	75	100
Cement (kg/m³)	583	583	583	583	583
Sand (kg/m³)	603	603	603	603	603
Gravel (kg/m³)	904	678	452	226	0
RCA. (kg/m³)	0	226	452	678	904
Free-water (kg/m³)	230	230	230	230	230
Synthetic Macro Fibre - 0.11% by volume of concrete (kg/m³)	1	1	1	1	1
Microsilica - 10% by weight of cement (kg/m³)	58.4	58.4	58.4	58.4	58.4
Superplasticiser by weight of cement (kg/m³)	3.50	3.50	3.50	4.66	4.66

RCA ---- Recycled Coarse Aggregate, F --- Fibre, M --- Microsilica

Table 12: Concrete mix details – Series 6 (0.11% F, 15% M)

Recycle Aggregate by weight of coarse aggregate. (%)	0	25	50	75	100
Cement (kg/m³)	583	583	583	583	583
Sand (kg/m³)	603	603	603	603	603
Gravel (kg/m³)	904	678	452	226	0
RCA. (kg/m³)	0	226	452	678	904
Free-water (kg/m³)	230	230	230	230	230
Synthetic Macro Fibre - 0.11% by volume of concrete (kg/m³)	1	1	1	1	1
Microsilica - 15% by weight of cement (kg/m³)	87.6	87.6	87.6	87.6	87.6
Superplasticiser by weight of cement (kg/m³)	4.66	4.66	4.66	5.83	5.83

RCA ---- Recycled Coarse Aggregate, F --- Fibre, M --- Microsilica

Table 13: Concrete mix details – Series 7 (0.11% F, 20% M)

Recycle Aggregate by weight of coarse aggregate. (%)	0	25	50	75	100
Cement (kg/m³)	583	583	583	583	583
Sand (kg/m³)	603	603	603	603	603
Gravel (kg/m³)	904	678	452	226	0
RCA. (kg/m³)	0	226	452	678	904
Free-water (kg/m³)	230	230	230	230	230
Synthetic Macro Fibre - 0.11% by volume of concrete (kg/m³)	1	1	1	1	1
Microsilica - 20% by weight of cement (kg/m³)	116.8	116.8	116.8	116.8	116.8
Superplasticiser by weight of cement (kg/m³)	6.41	6.41	6.41	7.00	7.00

RCA ---- Recycled Coarse Aggregate, F --- Fibre, M --- Microsilica

3.3 Concrete mixing and placing

Winget Croker Cumflow RP50XD Rotating Pan mixer was used for the concrete mixing. The fine aggregate was divided into two halves. The first half was placed at the bottom of the concrete mixer pan followed by addition of calculated amount of cementitious materials from mix design and this was subsequently covered with remaining half measured quantity of fine aggregate (sand). The cementitious materials was thoroughly and evenly dispersed in the mix and these combinations was dry mix for about 60s. Thereafter, the entire measured quantity of natural and recycled coarse aggregate were poured into the concrete mixer simultaneously and thoroughly dry mix for another 60s in order to ensure the concrete materials are well-blended together. Synthetic macro fibres were dispersed into the mixer and equally dry mixed together for about 60s in order to ensure uniform dispersion of fibres in the mix. Thereafter, free-water incorporating superplasticizer was gradually added to the concrete materials in the mixer and the constituents in the mixer were further mixed for about 120s.

After a clear assessment of the consistency and slump test, concrete was portioned in various designated lubricated moulds (cubes, cylinders, prisms) shown in table 5 in two layers with each layers compacted using the vibrating table in order to expel any entrapped air. The surface was gradually levelled with steel hand trowel and covered with polyethylene bag for 24hrs to prevent early loss of moisture. The concrete samples were thereafter de-moulded and cured in the water tank at about 20°C.

3.3.1 Sequence of laboratory work

a. Determination of saturated surface dry (ssd) density of natural fine aggregate, natural coarse aggregate, & recycled coarse aggregate;
b. Comparison of water absorption in each of the aggregates;
c. Adjustment of concrete mix design with the results obtained in (a) above;
d. Concrete batching;
e. Fresh concrete testing (Slump test);
f. Filling of steel moulds (cube, prism, and cylinder) and compaction using vibrating table;
g. Covering fresh concrete filled moulds with polyethylene bag to prevent loss of moisture due to evaporation;
h. De-moulding of concrete samples after 24hours;
i. Storage of hardened concrete samples in the curing tank at about 20ºC for maximum 28 days;
j. Testing of hardened concrete at 1, 7, and 28-day curing age respectively.

3.3.2 Testing of Aggregates and Concrete

Tests were performed on aggregates (natural fine, natural coarse and recycled coarse) in order to determine their particle density and water absorption respectively. Similarly, testing of the concrete samples in both fresh and hardened state were conducted in accordance to relevant standards. The object of the testing was to determine the workability (slump), compressive (cube) strength, flexural strength, tensile splitting strength, modulus of elasticity, water permeability (Autoclam), and fatigue performance for the purpose of evaluating the properties of concrete. Details of these tests are given below.

3.3.2.1 Particle Density and Water Absorption

The test procedure to determine the particle densities and water absorption capacity of fine aggregate, natural and recycled coarse aggregate was conducted in accordance to BS-EN-1097-6 (2013). The aim of the test was to determine the weight and volume of the aggregate and also the quantity of water that would be absorbed by the fine and coarse aggregate in the mixture in order to adjust the amount of free-water required to aid workability during mixing. Figure 14 displayed the particle density apparatus set-up (wire basket and pyknometer method) used for recycled coarse aggregate, natural coarse aggregate, and natural fine aggregate shown in Figure 15 respectively at saturated surface dry (ssd) condition.

(a) (b)

Figure 9: Particle density apparatus – (a) wire basket method (b)pyknometer method

(a) (b) (c)

Figure 10: Aggregate at Saturated Surface Dry (SSD) condition – (a) Recycled aggregate, (b) Crushed Gravel, and (c) Sand.

3.3.2.2 Particle Size Distribution – Sieving method

Sieve analysis was conducted in conformity with BS-EN-933-1 (2012). The aim was to establish the particle grading and description of properties of fine and coarse aggregates used for concrete in order to ensure they are acceptable for concrete work and prevent any influence on fresh or hardened state characteristics of the concrete produced. A nested column of standard sieves were fitted and arranged together in order of decreasing aperture sizes. This arrangement comprises of sieve sizes 14mm to 2.36mm for coarse aggregate, while sieves with aperture between 5mm to 0.15mm were used for fine aggregate. 2kg of oven dry samples of natural and recycled coarse aggregate were poured into separate sieve columns arrangement respectively while the quantity of oven dry fine aggregate used for the test was 1kg. The sieves were shaken mechanically using the sieve shaker as shown in figure 16.

Figure 11: Set of sieves on sieve shaker

The retained materials in each sieve was weighed and recorded as a percentage of the initial oven dry mass while cumulative percentage retained and percentage passing were also calculated. The graphical representation of percentage passing against sieve apertures was plotted in logarithmic scale and analysed to determine the particle size distribution of these materials.

3.3.2.3 Slump test

Slump refers to the measure or an indicator of workability of concrete. It is the most widely known test to evaluate the workability of fresh concrete which is inexpensive and simple to perform. The workability of the fresh concrete was measured in accordance to BS-EN-12350-2 (2009) using the standard apparatus for each mix in all the series in order to show the concrete consistency. The apparatus includes slump cone mould, flat non-absorbent horizontal base plate, and steel tamping rod. The internal surface of the conical mould was dampened, thoroughly cleaned and lubricated with oil. The mould thereafter was placed on the non-absorbent horizontal base plate and filled in three layers with freshly mixed concrete from Winget Croker rotating pan mixer. Each of these layers received 25 blows using tamping rod. The vertical difference between the highest point at the centre of the subsided (slumped) concrete and the top of the mould was recorded as slump value as illustrated in figure 17.

illustrated in figure 17.

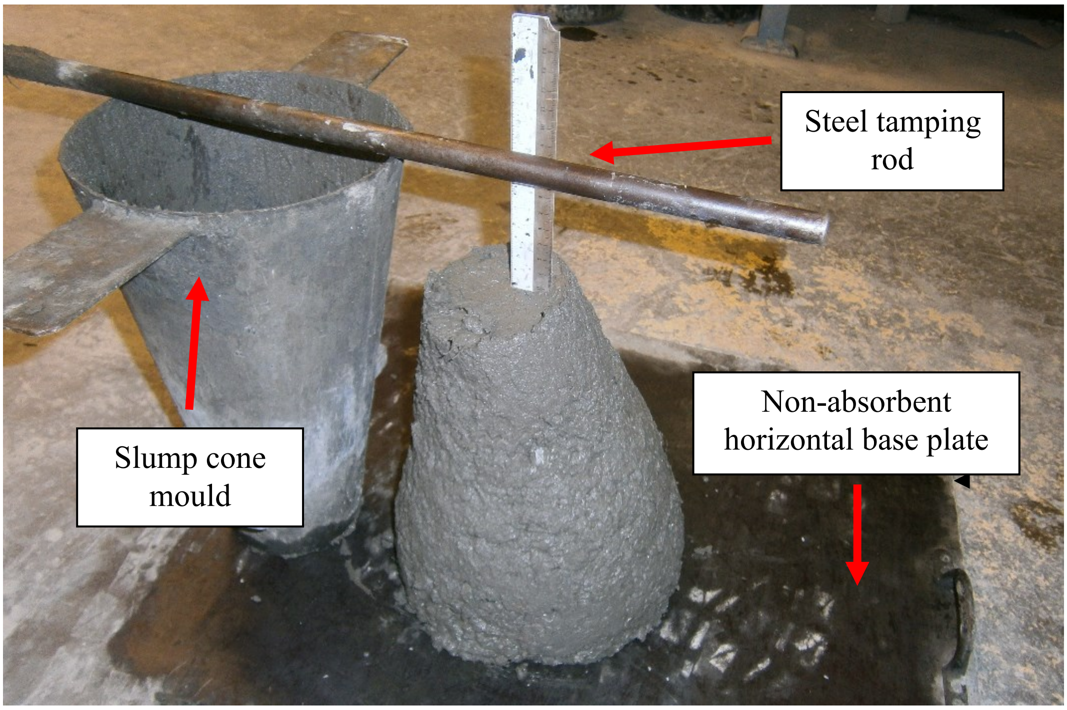

Figure 12: Slump measurement (True slump)

3.3.2.4 Compressive Strength Test

This is usually carried out with the ultimate aim of determining the compressive strength of hardened concrete at 28-day curing age and it remains the only engineering property of concrete that is usually specified. The compressive strength has a relationship with most other mechanical properties of hardened concrete and it also provides the basis for their estimation. This test is referred to as the greatest resistance of concrete cube to applied axial loading from the compression machine. Compressive strength test was conducted to determine the greatest resistance at failure of concrete cube samples to applied axial loading. Three standard 100x100x100mm cube samples were prepared per mix in each series for phases 1, 2, and 3 respectively. These samples were tested to failure using digital Avery-Denison compression testing machine shown in figure 18 at a constant loading rate of 3.2kN/s.

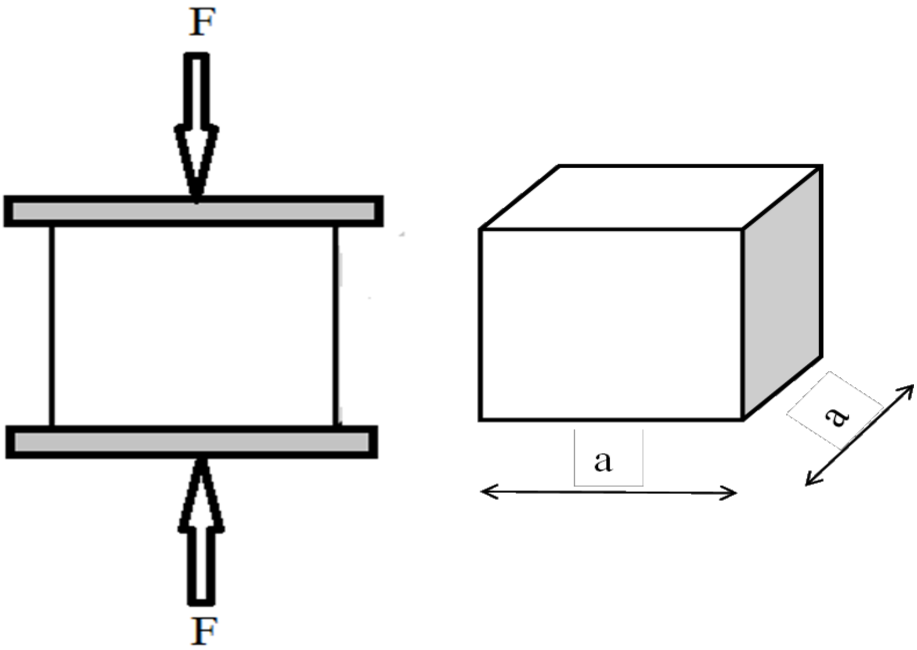

Figure 13: Schematic illustration of Compressive strength test

The test was performed on three concrete cube samples in accordance to BS-EN-12390-4-2009 at 1, 7, and 28-day curing age respectively. The average compressive strength of these cubes was obtained by using the relationship between the maximum load at failure and the cross sectional area of the concrete cubes as expressed by the equation $fc = F/A$. [Where fc represents the compressive strength, F represent the maximum load at failure (N), and A stands for the cross sectional area of the concrete cube sample (mm^2)].

3.3.2.5 Flexural Strength Test

Flexural strength test is an indirect method often used to determine the tensile strength of concrete. It is often expressed as concrete modulus of rupture. Three 100x100x500mm hardened concrete prism samples were cured in water at 20ºC and tested to failure using Denison testing machine shown in figure 19 at 1, 7, and 28-day curing age respectively.

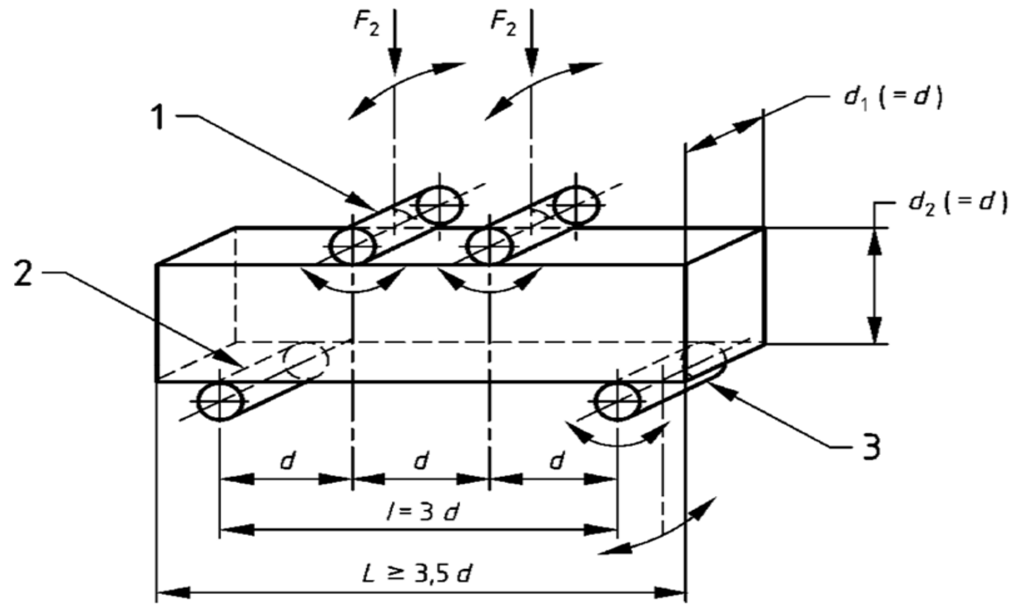

Figure 14: Schematic illustration of flexural strength test (two-point loading) set-up after BS-EN-12390-5-2009

The test was conducted in accordance to BS-EN-12390-5-2009 using two-point loading arrangement and the maximum load at failure was recorded. The flexural strength was calculated from the mean of the three recorded results using the equation f_{cf} = (FxI) / (d_1xd_2) [Where f_{cf} represent the flexural strength, F stands for the maximum load at failure (N), I is the distance between the supporting rollers (Farjadmand and Safi), and d_1 & d_2 are lateral dimensions of the sample (Farjadmand and Safi)]. The load was gradually applied at intial stage and subsequently increased until the loading blocks were brought into contact with the upper surface of the prism. It was ensured that all loading and supporting rollers were resting evenly against the concrete sample with the reference direction of loading perpendicular to the direction of casting of the prism samples.

3.3.2.6 Tensile Splitting Strength Test

Tensile splitting strength is one of the significant properties of concrete. It was performed in order to determine the tensile resistance of concrete rather than direct tensile strength test due to ease of testing. It is mostly performed on cylindrical concrete samples of 150mm diameter and 300mm long. Three hardened cylindrical concrete samples of 100mm Ø and 200mm high were prepared per mix in each series for phases 1, 2, and 3 respectively. The Concrete samples were tested to failure using Denison testing machine shown in figure 20 at 1, 7, and 28-day curing age respectively in accordance to BS-EN12390-6-2010.

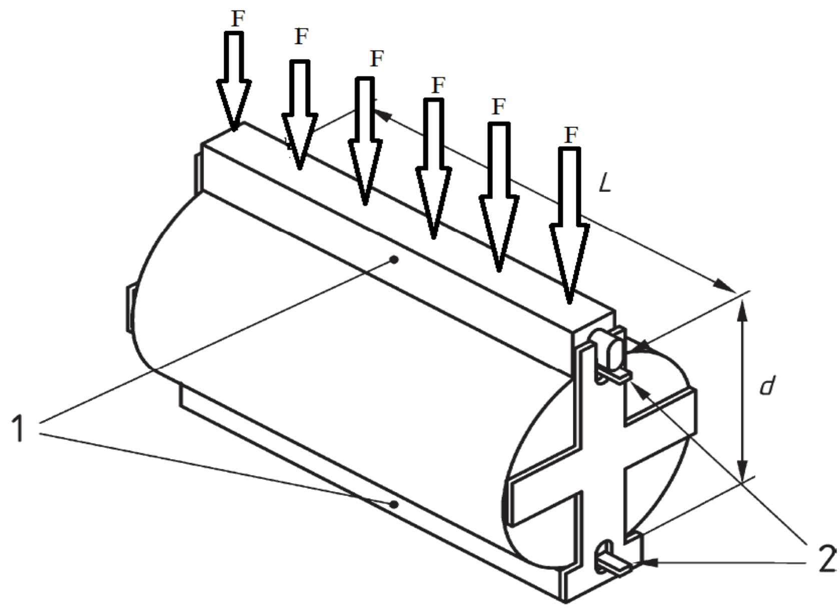

Figure 15: Schematic illustration of Tensile splitting strength test set-up after BS-EN-12390-6-2009

The Denison testing machine was lowered until the platen came into contact with the top surface of the concrete sample. Loading was gradually applied at initial stage and thereafter increased continuously until failure occurred. The maximum load at failure was recorded and the mean tensile splitting strength was calculated from the equation

$f_{ct} = (2xF)/(\pi xLxd)$ [Where f_{ct} represent the tensile splitting strength, F is the maximum average load at failure (N), L stands for the length of line of contact of sample, and d is the designated cross sectional dimension].

3.3.2.7 Static Modulus of Elasticity

Static Modulus of Elasticity was carried out on three hardened cylindrical concrete samples of 100mm Ø and 200mm high prepared per concrete mix in each series for phases 1, 2 and 3, respectively. These samples were cured in water at 20ºC for 28-day curing age and tested to failure using Denison compression testing machine and strain measuring apparatus (CT534 - Compressometer) shown in figure 21. The test complied with BS-1881-121-1983

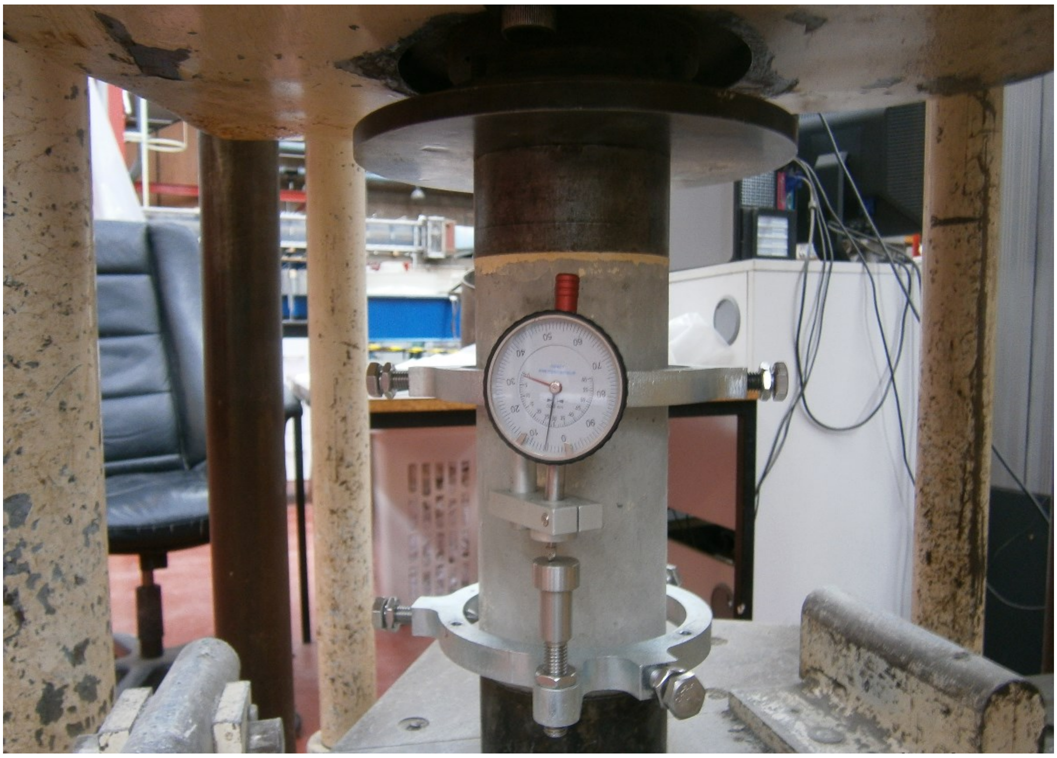

Figure 16: Static modulus of elasticity test set-up

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3.3.2.8 Water Permeability Test

This is measured as inflow of water under a reducing or constant pressure gradient (Beushausen and Luco, 2015). Sorptivity test was carried out in order to determine the cumulative inflow of water permeability index of the hardened concrete cube samples as a measure of assessing the surface characteristics of concrete which influence durability and performance. Three standard 100x100x100mm concrete cube samples were prepared per concrete mix in each concrete Series in Phase 2 and Phase 3 respectively and were tested using the Autoclam permeability system. Figure 22 displays the connection between concrete sample and autoclam equipment used for the test.

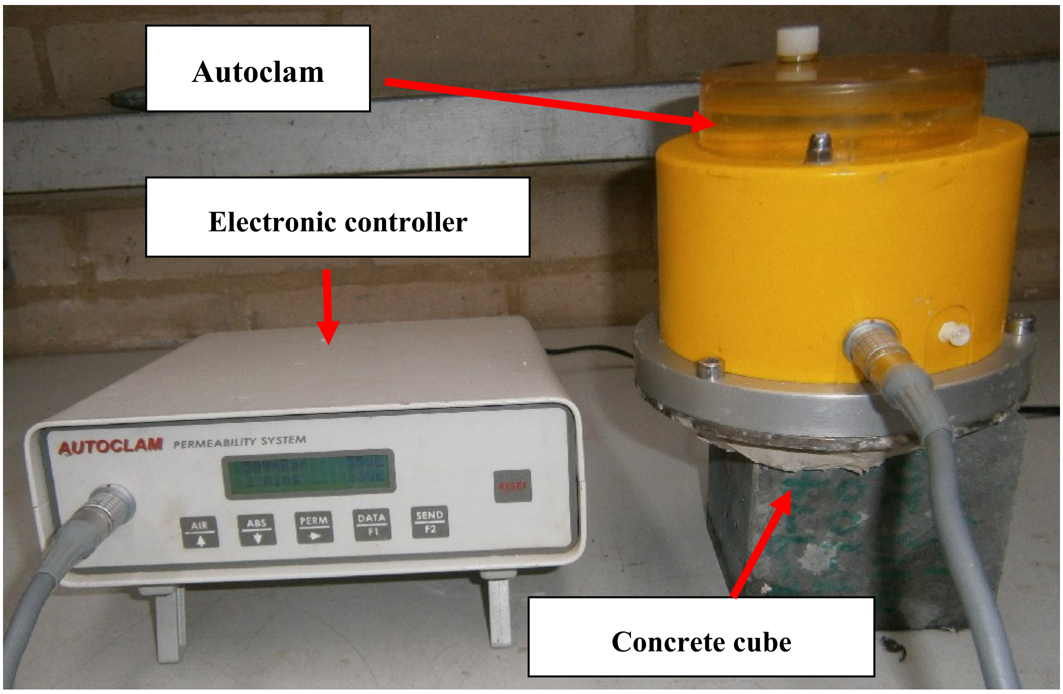


Figure 17: Autoclam permeability test set-up

The concrete cube samples were kept on the laboratory table for a week after removal from curing tank in order to ensure samples are sufficiently air dried before conducting the test. The test complied with the operating manual of the Autoclam system developed at Queen's University Belfast. A metallic base ring, 50mm internal diameter was bonded to the test surface (one side of the cube) using adhesive.

The autoclam body which contains the pressure transducer that records the test pressure is bolted to the base ring with an O-ring thus providing the seal between the ring and the body during the test in order to ensure there is tightness between the concrete suface and auntoclam chamber. The transparent plastic reservoir is filled with potable water and thereafter when the Autoclam has been fully attached to the base ring as indicated by the prompt on the electronic controller panel the pressure increased to 2kPa (0.02 bar). The Autoclam system automatically began to allow water inflow into the concrete samples at a constant pressure of 2kPa (0.02 bar) while the pressure inside the autoclam chamber was also kept constant at 50kPa (0.5 bar) respectively.

The test was conducted for 15 minutes and the cumulative volume of water penetrated into the concrete was automatically recorded and stored by the electronic controller. The average cumulative volume of water inflow into the three concrete cubes at different pressure was plotted against the square root of time between 5th-15th minutes as recommended by the operating manual. The graph shows a linear correlation, while the gradient obtained from the equation of the regression line was taken as the sorptivity index expressed in $m^3/min^{0.5}$.

3.3.2.9 Flexural Fatigue Assessment

Flexural fatigue performance was conducted to determine the fatigue behaviour of high performance recycled aggregate concrete incorporating synthetic macro fibre under cyclic loading. The aim was to determine the fatigue parameters from the number of cycles at a given fluctuating stress and strain that the samples can sustain before failure occurs. The test involved application of load on concrete prism samples at pre-determined stress level and in this case four levels of maximum stress (0.95, 0.85, 0.75 & 0.65) respectively. The stress levels were based on ultimate static strength recorded before the fatigue testing commenced. Fifteen hardened concrete prism of dimension 100x100x500 mm were prepared for each mix in series 6 (i.e. 75 samples in total). These samples were subjected to three-point flexural test under static and fatigue loading using a 50kN servo-hydraulic digital control actuator shown in figures 23 and 24 respectively. The target fatigue cycle is 100,000 due the time consuming nature of the test while frequency is 3Hz. The test was conducted on the non-trowel side of the concrete prism.

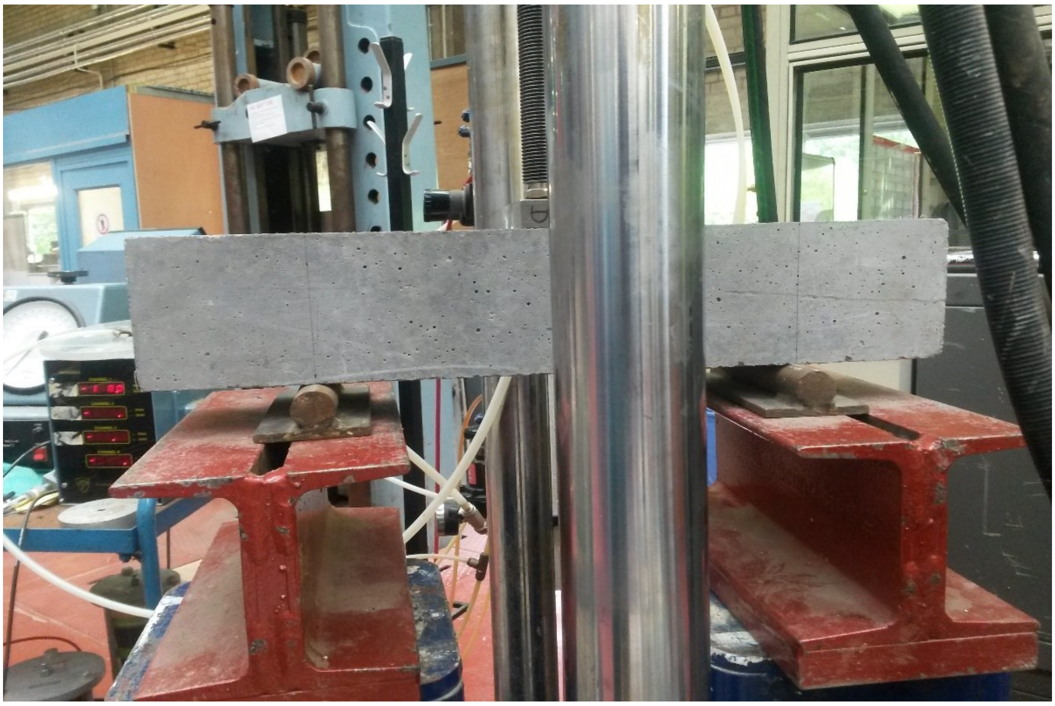


Figure 18: Fatigue test set-up

Figure 19: Servocon hydraulic control for fatigue test

The test was repeatedly done with three identical samples at different fluctuating loads per mix design. The mean load & amplitude defines the cyclic application of the load between upper and lower load. The cycles were loaded at a standard rate of 0.5mm/min and frequency of 3Hz. The stress levels were plotted against the average number of cycles obtained from the testing in order to determine the S_{max}-N_f relationship and fatigue life.

4 FRESH AND HARDENED PROPERTIES OF RECYCLED AGGREGATE CONCRETE WITH SYNTHETIC MACRO FIBRE

4.1 Introduction

This chapter describes details of one of the objectives of this research work, to assess the effect of incorporating 54mm Forta-Ferro synthetic macro fibre on the physical and mechanical characteristics of concrete produced with partial and full replacement of natural coarse aggregate by recycled coarse aggregate. Chapter 3 provide details of all conducted tests under this chapter. The percentage substitution of natural coarse aggregate by recycled coarse aggregate in the concrete mix are 0%, 25%, 50%, 75%, and 100% by weigth of coarse aggregate respectively. The concrete mix also incorporates 4.5kg/m³ (0.5%) and 1kg/m³ (0.11%) synthetic macro fibre by volume of concrete. The design concrete mix had 28-day characteristic cube strength of 50MPa with a target mean compressive strength of 63.1MPa and high workability of 60-180mm at free-water/cement ratio of 0.39 as shown in Table 66. The results, discussion and summary of findings obtained from aggregates testing, (particle density and water absorption test), fresh concrete sample testing (slump) and hardened concrete specimens testing (compressive strength test, flexural strength test, tensile splitting strength test, and static modulus of elasticity) are all described respectively in this chapter.

About four hundred and fifty (450) concrete specimens, comprising 135 cubes, 135 prisms, and 180 cylinders respectively were tested. Tables 6-8 in Chapter 3 show the concrete mix details. Series 1 represent the control experiment and does not have any fibre addition while Series 2 and 3 consists of 4.5kg/m³ and 1kg/m³ synthetic macro fibre respectively. The author anticipated that the inclusion of synthetic macro fibre in the concrete mix would improve the compressive cube strength of the concrete sample in Series 2 and 3 respectively. The manufacturer (Forta-Ferro Corporation) recommended a dosage rate of 1kg/m³ while the author chose a higher dosage rate of 4.5kg/m³ in order to carry out an assessment of the impact of both low and higher dosage rate of the fibre on fresh and hardened concrete properties.

4.2 Impurities in Recycled Coarse Aggregate

The performance of recycled coarse aggregate can be reduced due to the presence of impurities, which emanated from demolition process including porous mortar and cement paste attached to the parent aggregate. The effect could also lead to general reduction in physical and mechanical characteristics of recycled aggregate concrete. Figure 20 shows some of the impurities identified through visual inspection from the recycled coarse aggregate supplied by Coleman and Co. Birmingham. The average mass and equivalent percentage of impurities found in three separate 100g recycled coarse aggregate visually inspected are displayed in Table 14.

Figure 20: Some impurities found in recycled coarse aggregate

Table 14: Average percentage impurities

Type of Impurity	Average percentage (%)
Glass	1.1
Metal	1.0
Wood	0.4
Ceramic	1.5
Others	1.2
Total	5.2

The average percentage impurities present in the recycled coarse aggregate amounted to about 5% of the total mass of the sample. Although there is visual evidence to show the presence of adhered mortar on the parent material, it was practically impossible to estimate their percentage. However, the adhered mortar does not seems to be of significant quantity but its impact on the physical and mechanical characteristics of recycled coarse aggregate concrete cannot be neglected.

4.3 Particle Density and Water Absorption of Aggregates

The results of particle density and water absorption for natural and recycled coarse aggregates are given in Table 18. The particle density of recycled coarse aggregate under saturated surface dry (ssd) and oven dried conditions were 2323kg/m^3 and 2158kg/m^3 respectively, which represents 7% and 13% reduction in particle density results for natural coarse aggregate which are 2505kg/m^{3}and 2470kg/m^3 respectively, under same conditions. The low-density nature of adhered mortar on recycled aggregate from the parent concrete materials was responsible for these differences. Similar observation was suggested by Rao et al. (2011) and Yang et al. (2011). These occurred due to the lower density, lightness, and porous nature of the attached mortar to parent aggregates. The water absorption for both recycled coarse aggregate and natural coarse aggregate were 7.65% and 1.44% respectively. This implies that, the water absorption of recycled aggregate was about five (5) times higher than the corresponding natural gravel.

Table 15: Result of particle density and water absorption

Aggregate	Natural Coarse (Gravel)	Natural Fine (Sand)	Recycled Coarse
Particle density (Oven dry) (kg/m^3)	2470	2208	2158
Particle density (SSD) (kg/m^3)	2505	2445	2323
Water absorption (%)	1.44	1.67	7.65

This result was due to the presence of larger pores in recycled coarse aggregate. Limbachiya et al. (2004) and Kikuchi et al. (1993) reported that water absorption of recycled coarse aggregate was between 3–5 times more than natural coarse aggregate, a result which was attributed to attached cement paste on recycled concrete aggregate. Natural sand had particle density of 2445kg/m³ and 2408kg/m³ at saturated surface dry (ssd) and oven dry state respectively with a water absorption of 1.67.

4.4 Particle size distribution (PSD) – Sieve Analysis

4.4.1 Natural coarse aggregate

The percentage passing of natural coarse aggregate through the standard sieve apertures (10mm and 5mm) was 87.4% and 13.9% respectively as shown in Table 16.

According to BS-EN-12620 (2013) the coarse aggregate lies within the single-sized aggregate grading limits for 10mm. About 212.8g was retained in the sieve aperture 2.36mm, which represent about 10.6% of the overall mass of the oven dry natural coarse aggregate sample used for the sieve analysis.

Table 16: Sieve analysis for natural coarse aggregate

Sieve size (mm)	Mass Retained (g)	Percentage retained (%)	Percentage passing (%)	Single-sized aggregate limits for 10mm
14.00	0.00	0.00	100.0	100
10.00	252.60	12.63	87.37	85-100
5.00	1469.00	73.45	13.92	0-25
2.36	212.80	10.64	3.28	0-5
<2.36	65.60	3.28	0.00	
Total	2000	100		

The effective sizes (D10, D30, & D60), coefficient of gradation (Cc) and uniformity coefficient (Cu) were all determined from the particle-size distribution curve presented in figure 26.

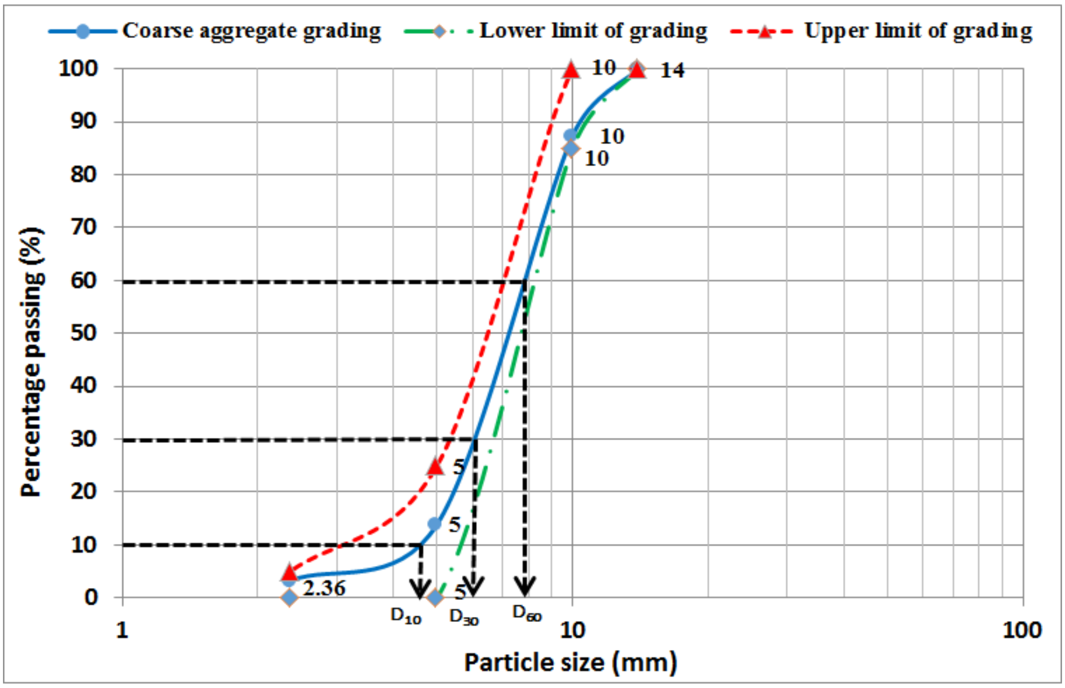


Figure 21: Grading curve of natural coarse aggregate (Crushed gravel)

From Figure 21, the effective sizes corresponding to 10%, 30%, and 60% percentage finer are D_{10} = 4.8mm, D_{30} = 6mm, D_{60} = 7.9mm respectively. The calculation of coefficient of gradation (Cc) and uniformity coefficient (Cu) are shown below using the values obtained from the effective sizes.

i. Uniformity coefficient - $C_U = D_{60}/D_{10} = 7.9/4.8 = 1.65$

ii. Coefficient of gradation - $C_C = D_{30}^2/(D_{10}xD_{60}) = 6^2/(4.8x7.9) = 0.95$

According to BS-EN-12620 (2013), the value of 1.65 obtained from the uniformity coefficient indicates that the natural coarse aggregate used for concrete work is well graded.

4.4.2 Natural fine aggregate

Table 20 reveals the result of sieve analysis conducted on fine aggregate. About 369g was retained in the 0.15mm sieve which represents about 36.9% of the total mass of the oven dry sample used. Approximately, 74% of the fine aggregate passed through the 0.6mm sieve aperture. This value of percentage passing 0.6mm sieve aperture was used as the value for grading of fine aggregate in the concrete mix design in order to determine the proportion of fine aggregate content required in the concrete mix. According to BS-EN-12620 (2013), the fine aggregate used is acceptable for concrete because it is within the medium grading limits for 10mm.

Table 17: Sieve analysis for fine aggregate

Sieve size (mm)	Mass Retained (g)	Percentage retained (%)	Percentage passing (%)	Medium grading limits for 10mm
5.00	35.20	3.52	96.48	
2.36	152.60	15.26	81.22	65-100
1.18	45.00	4.50	76.72	45-90
0.60	27.50	2.75	73.97	25-80
0.30	270.00	27.00	46.97	5-48
0.15	368.50	36.85	10.12	
<0.15	101.20	10.12	0.00	
Total	1000	100		

The effective sizes (D_{10}, D_{30}, & D_{60}), coefficient of gradation (Cc) and uniformity coefficient (Cu) were all determined from the particle-size distribution curve presented in figure 27.

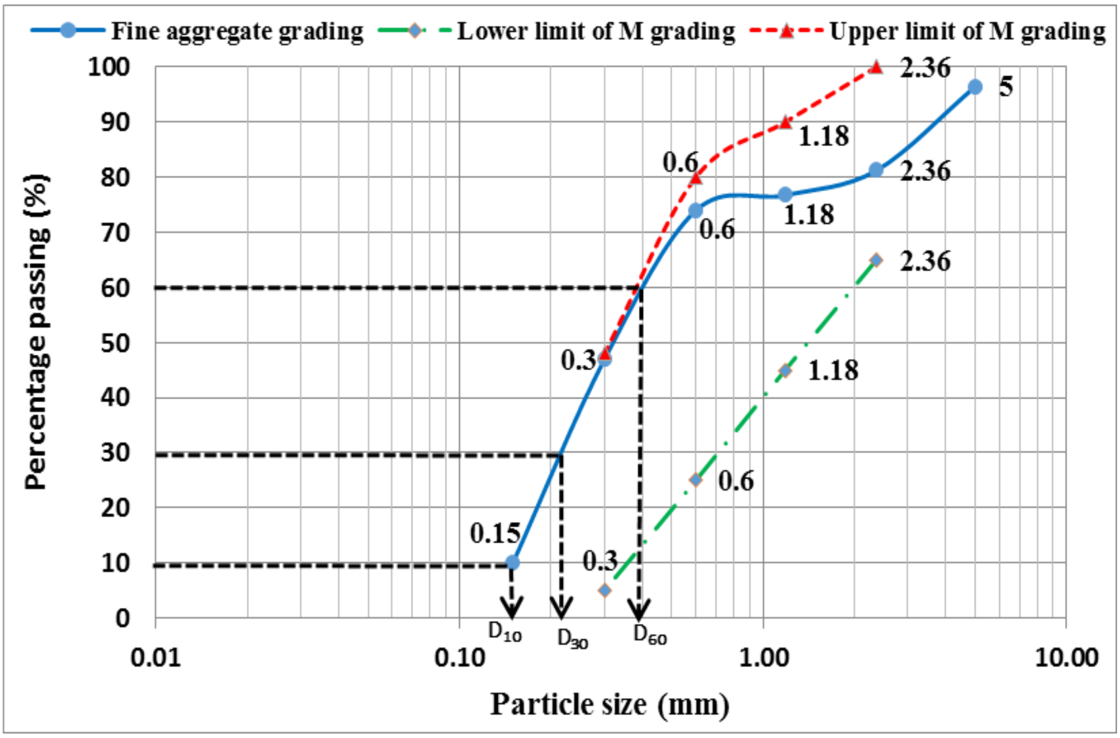


Figure 22. Grading curve of fine aggregate (sand)

From figure 27, the effective sizes corresponding to 10%, 30%, and 60% percentage finer are D_{10} = 0.15mm, D_{30} = 0.22mm, D_{60} = 0.4mm respectively. The coefficient of gradation (Cc) and uniformity coefficient (Cu) are calculated using the values obtained from the effective sizes.

i. Uniformity coefficient - $C_U = D_{60}/D_{10} = 0.4/0.15 = 2.67$

ii. Coefficient of gradation - $C_C = D_{30}^2/(D_{60}xD_{10}) = 0.22^2/(0.15x0.4) = 0.81$

4.4.3 Recycled coarse aggregate

The percentage of recycled aggregate passing through the standard sieve sizes (10mm, 5mm, and 2.36mm) were 90.4%, 24.2% and 4.15% respectively as indicated in Table 18. This shows that the recycled coarse aggregate lies within the specified range of single-sized aggregate grading limits for 10mm in BS-EN-12620. Sieve size 5mm retained the largest portion of the oven dry sample of about 1325g, which represents 66.3% of the total mass of sieved recycled coarse aggregate sample. A comparison with the natural coarse aggregate indicate that the percentage retained in sieve sizes 10mm and 5mm were more in natural aggregate than recycled aggregate.

Table 18: Result of sieve analysis for recycled coarse aggregate

Sieve size (mm)	Mass of Soil Retained (g)	Percentage retained (%)	Percentage passing (%)	Single-sized agg. limits for 10mm
14.00	0.0	0.00	100.00	100.0
10.00	192.00	9.60	90.40	85-100
5.00	1325.00	66.25	24.15	0-25
2.36	400.00	20.00	4.15	0-5
<2.36	83.00	4.15	0.00	
Total	2000	100		

The effective sizes (D_{10}, D_{30}, & D_{60}), coefficient of gradation (Cc) and uniformity coefficient (Cu) were all determined from the particle-size distribution curve presented in figure 23.

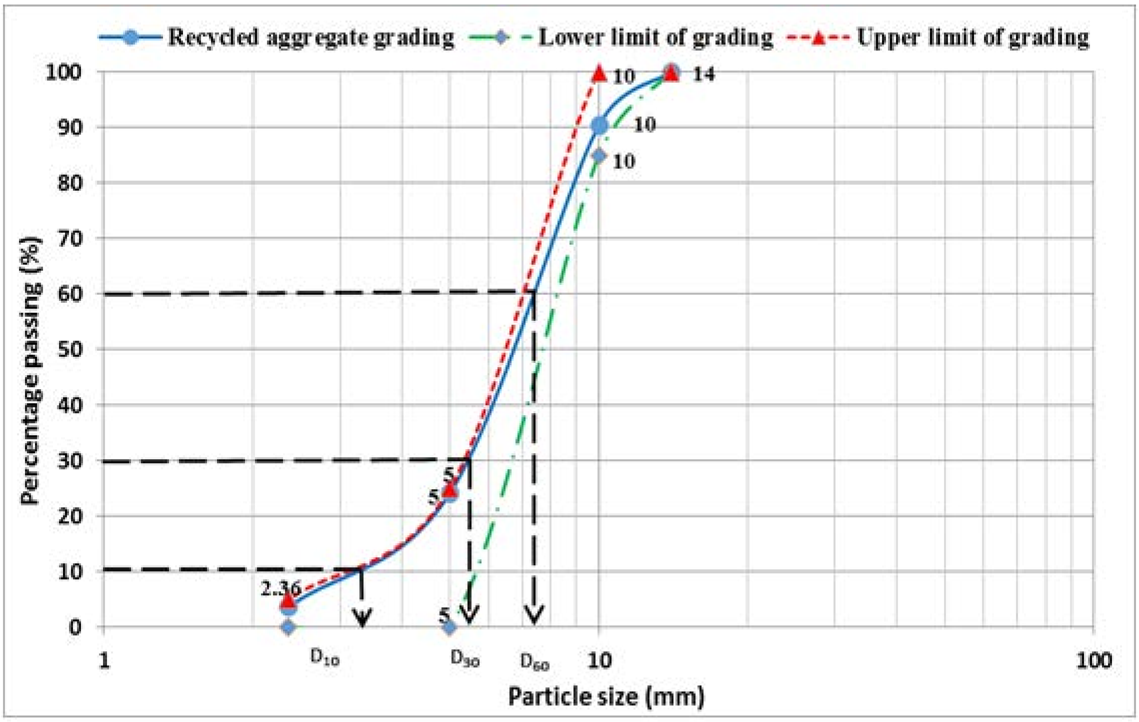


Figure 23. Grading curve of recycled coarse aggregate

The effective sizes corresponding to 10%, 30%, and 60% percentage finer are D_{10} = 3.3mm, D_{30} = 5.5mm, D_{60} = 7.5mm respectively. The calculations coefficient of gradation (Cc) and uniformity coefficient (Cu) are shown below using the values obtained from the effective sizes.

i. Uniformity coefficient - $C_U = D_{60}/D_{10} = 7.5/3.3 = 2.30$

ii. Coefficient of gradation - $C_C = D_{30}^2/(D_{10}xD_{60}) = 5.5^2/(3.3x7.5) = 1.22$

The value of 2.3 obtained from the uniformity coefficient indicates that recycled coarse aggregate is well graded and even more than the natural coarse aggregate.

4.5 Slump test

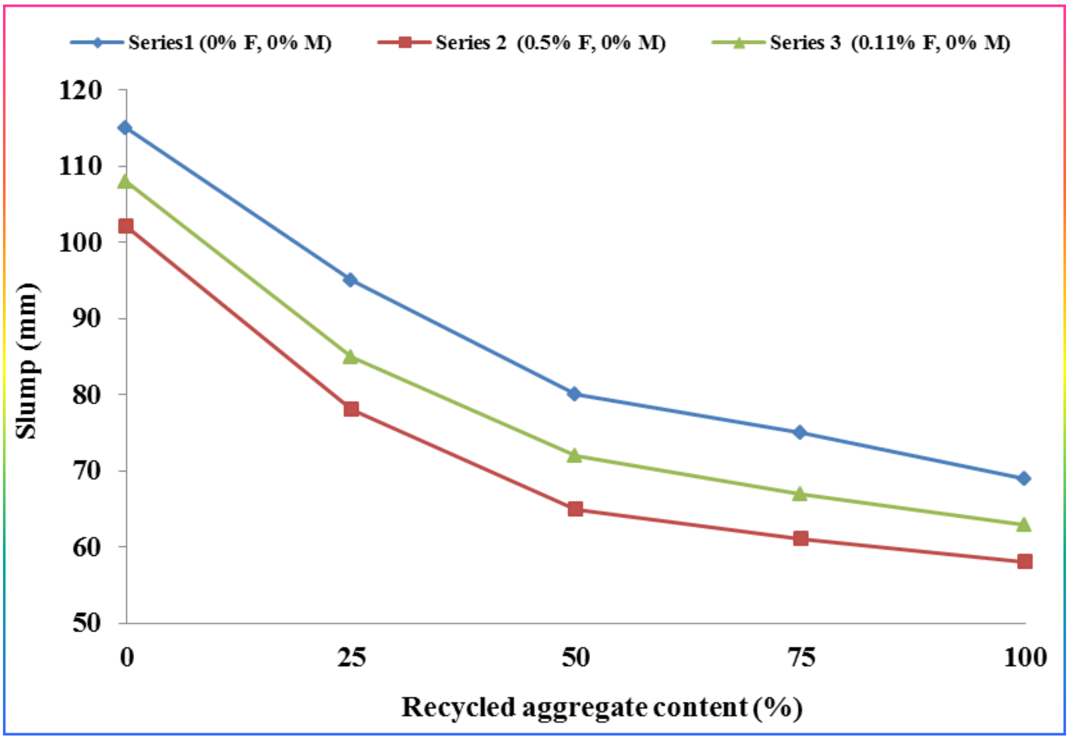
The results of workability test for each of the concrete mix incorporating 0%, 25%, 50%, 75%, and 100% recycle coarse aggregate respectively are given in Table 22 with graphical representation in figure 29.

Table 19: Result of slump test for Series 1-3 concrete mix

RCA (%)	Series 1 (0% F, 0% M) (mm)	Series 2 (0.5% F, 0% M) (mm)	Series 3 (0.11% F, 0% M) (mm)
0	115	102	112
25	95	78	91
50	80	65	76
75	75	61	71
100	69	58	66

RCA --- Recycled Coarse Aggregate, F --- Fibre, M --- Microsilica

Result in series 1 (control mix) indicated that the highest slump value of 115mm was achieved at 0% recycled coarse aggregate content while the least slump of 69mm which represents 40% reduction was recorded at 100% recycled coarse aggregate content. Results from Series 2 and 3 follows similar trend recorded in Series 1. The effect of higher water absorption associated with recycled coarse aggregate was responsible for the outcome. Similar observations were also reported by Topcu and Şengel (2004) and Etxeberria et al. (2007a). However, results from Series 1-3 lies within the design mix slump specification of 60-180mm with the exception of Series 2 at 100% recycled coarse aggregate content.



RCA --- Recycled Coarse Aggregate, F --- Fibre, M --- Microsilica

Figure 24. Effect of recycled coarse aggregate on workability of concrete for different fibre contents

A close comparison of the results across all the Series shows that workability decreases with increasing percentage content of recycled coarse aggregate in the concrete mix due to high rate of water absorption associated with recycled aggregate. This view was also corroborated by Zaidi (2009), Etxeberria et al. (2007a), and Patil et al. (2013). Figure 24 illustrates the decreasing trend in workability in Series 1-3 with increasing recycled aggregate content. The slump value of concrete mix in Series 2 decreased because of higher fibre dosage (0.5%) which rendered the concrete mix less workable. This was due to the large surface area of synthetic macro fibre, which consumed certain percentage of mortar and twisted around the particles of aggregates. Ramakrishnan et al. (1989a), Tattersall and Banfill (1983) also observed that concrete mix with higher dosage of fibre produced low workability due to interlocking of fibre and entrapped air.

Grace (2011), reported that synthetic macro fibres would consume some percentage of mortar due to the surface area and thus caused reduction in workability and creaminess of the concrete mix. The reduction in workability and dryness of recycled coarse aggregate, led to difficulty in compaction and surface finish of the concrete. The graph shows a wide gap between Series 1 and 2 due to the effect of more dosage rate of fibre with increasing percentage recycled aggregate content while the disparity between Series 1 and 3 is not much due to low fibre dosage rate. This confirms that the higher the fibre dosage the lower the workability and vice-versa.

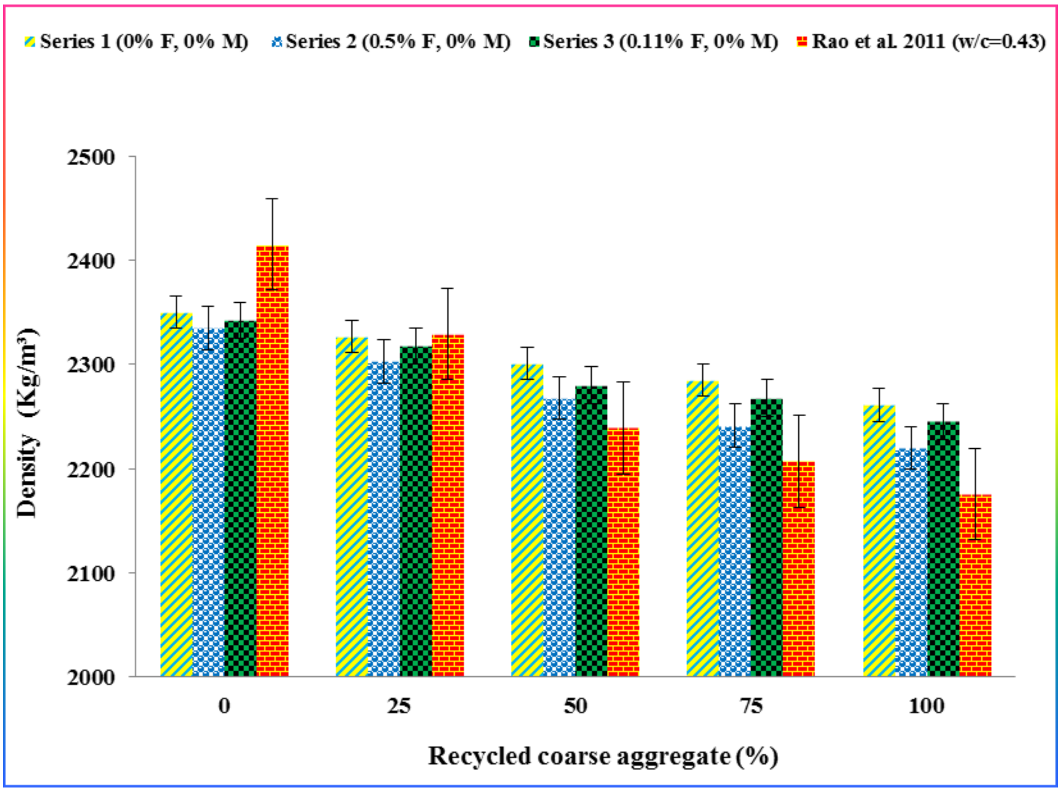
4.6 Density of concrete

The results of fresh concrete density and 28 days hardened concrete cubes densities for each of the concrete mix incorporating 0%, 25%, 50%, 75%, and 100% recycled coarse aggregate respectively are given in Tables 20 and 21 while the variations with increasing recycled aggregate content in different concrete mixes are illustrated in Figures 25 and 26 respectively.

Table 20: Fresh concrete density

RCA (%)	Series 1 (0% F, 0% M) (kg/m^3)	Series 2 (0.5% F, 0% M) (kg/m^3)	Series 3 (0.11% F, 0% M) (kg/m^3)
0	2350	2335	2342
25	2327	2303	2318
50	2301	2268	2280
75	2285	2241	2268
100	2261	2220	2245

RCA --- Recycled Coarse Aggregate, F --- Fibre, M --- Microsilica



RCA --- Recycled Coarse Aggregate, F --- Fibre, M --- Microsilica

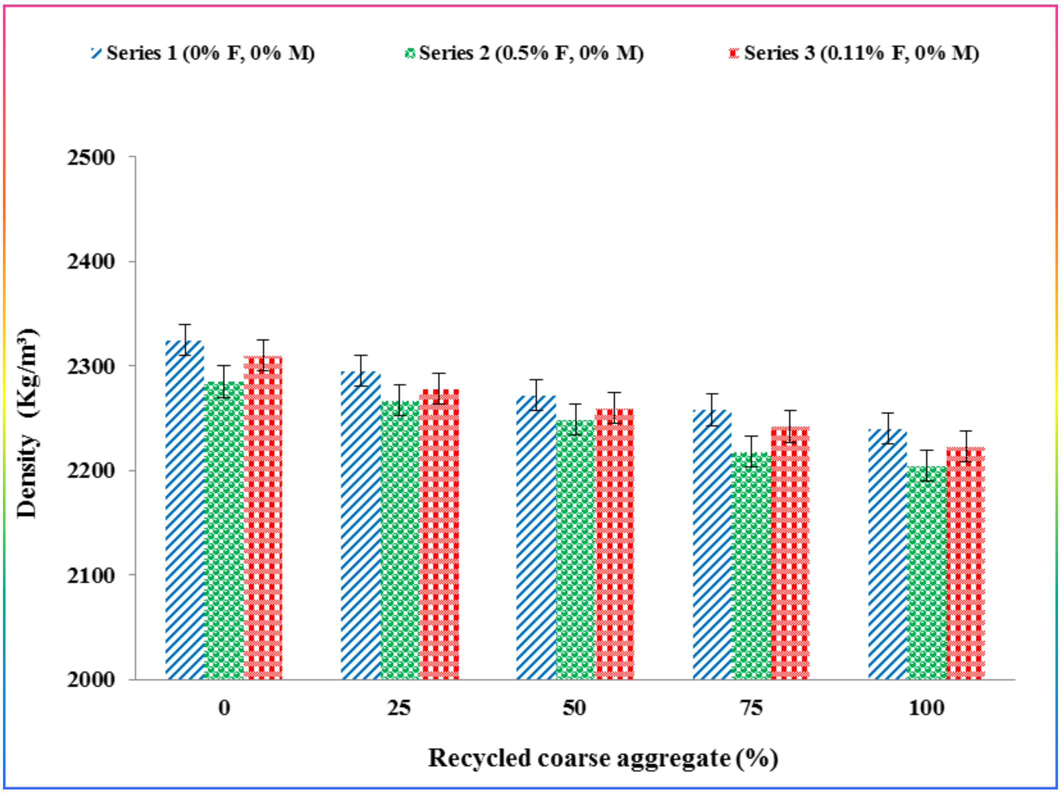
Figure 25: Variation in fresh concrete density with recycled coarse aggregate

The graph indicates that the density of concrete decreases with increase in recycled coarse aggregate content. This is due to the porous and light weight nature of recycled coarse aggregate. Rao et.al., (2011) also reported similar trend in reduction of density with increase in recycled aggregate content in concrete mix and attributed the observation to light weight and porous nature of old cement adhered to the recycled aggregate. Series 1 concrete mix without recycled aggregate produced the highest density while concrete mix in Series 2 with 0.5% synthetic macro fibre had the least fresh density. This could be attributed to the ability of fibre to entrain small amount of air due to the surface treatment in the cause of manufacturing.

Table 21: Density of hardened concrete cubes at 28-days

RCA (%)	Series 1 (0% F, 0% M) (kg/m³)	Series 2 (0.5% F, 0% M) (kg/m³)	Series 3 (0.11% F, 0% M) (kg/m³)
0	2396	2285	2310
25	2368	2267	2278
50	2342	2249	2260
75	2325	2218	2242
100	2301	2205	2223

RCA --- Recycled Coarse Aggregate, F --- Fibre, M --- Microsilica



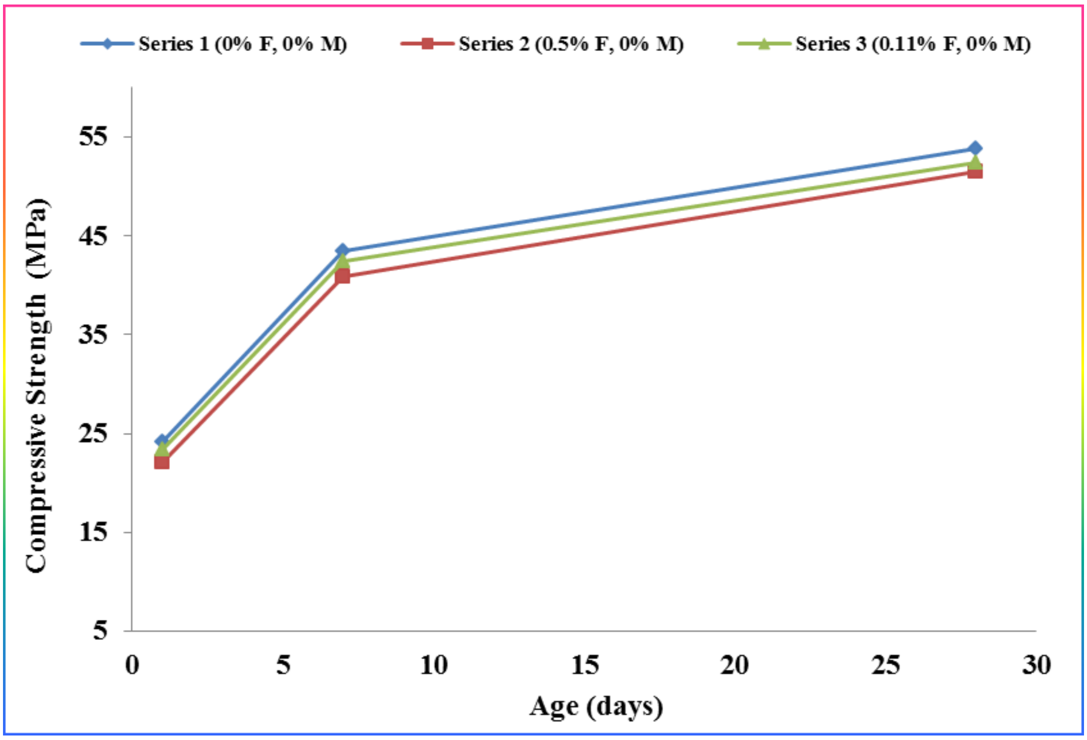
RCA --- Recycled Coarse Aggregate, F --- Fibre, M --- Microsilica

Figure 26: Variation in 28-days hardened concrete cube density with recycled coarse aggregate

Similar to results of fresh density shown in Figure 25, the density of hardened concrete cube specimen decreases with increase in recycled coarse aggregate content. This observation is due to the porous and light weight of recycled coarse aggregate. Series 1 concrete mix without recycled aggregate produced the highest density while concrete mix in Series 2 with 0.5% synthetic macro fibre had the least density. This could be attributed to the ability of fibre to entrain small amount of air due to the surface treatment in the cause of manufacturing.

4.7 Compressive cube strength test

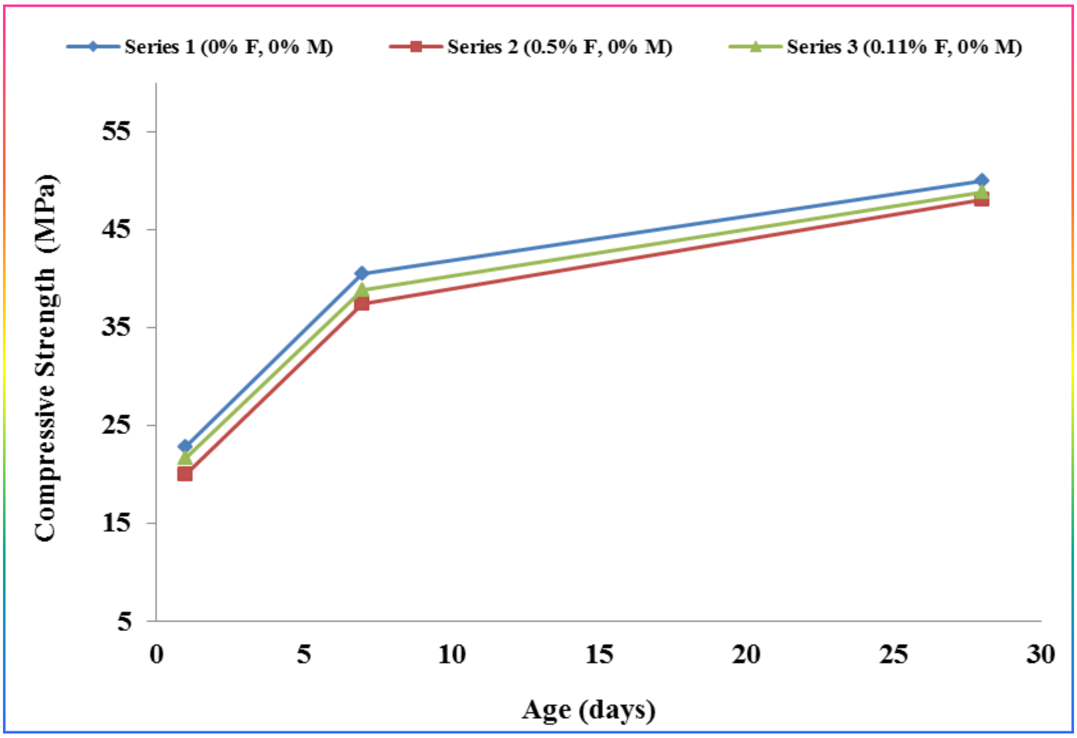
Figures 27-31 illustrate the compressive cube strength results of each concrete mix in Series 1-3 at 1, 7, and 28-day curing age respectively at different recycled coarse aggregate content.



RCA --- Recycled Coarse Aggregate, F --- Fibre, M --- Microsilica

Figure 27. Compressive cube strength at 0% recycled coarse aggregate content

Results from Series 1-3 illustrated in figure 28 produced the highest compressive cube strengths of about 54MPa, 50MPa, and 52MPa in series 1, 2, and 3 at 28-day curing age respectively. Although, the strength gained at 28-day curing age for concrete mix in Series 1-3 at 0% recycled coarse aggregate content exceeded the specified 28-day characteristic cube strength of 50MPa, none of these strength reached the target compressive cube strength of 63MPa. The results in Series 1 imply that concrete mix with no recycled coarse aggregate and synthetic macro fibre produced better results than Series 2 and 3 which incorporate recycled coarse aggregate and synthetic macro fibres respectively.

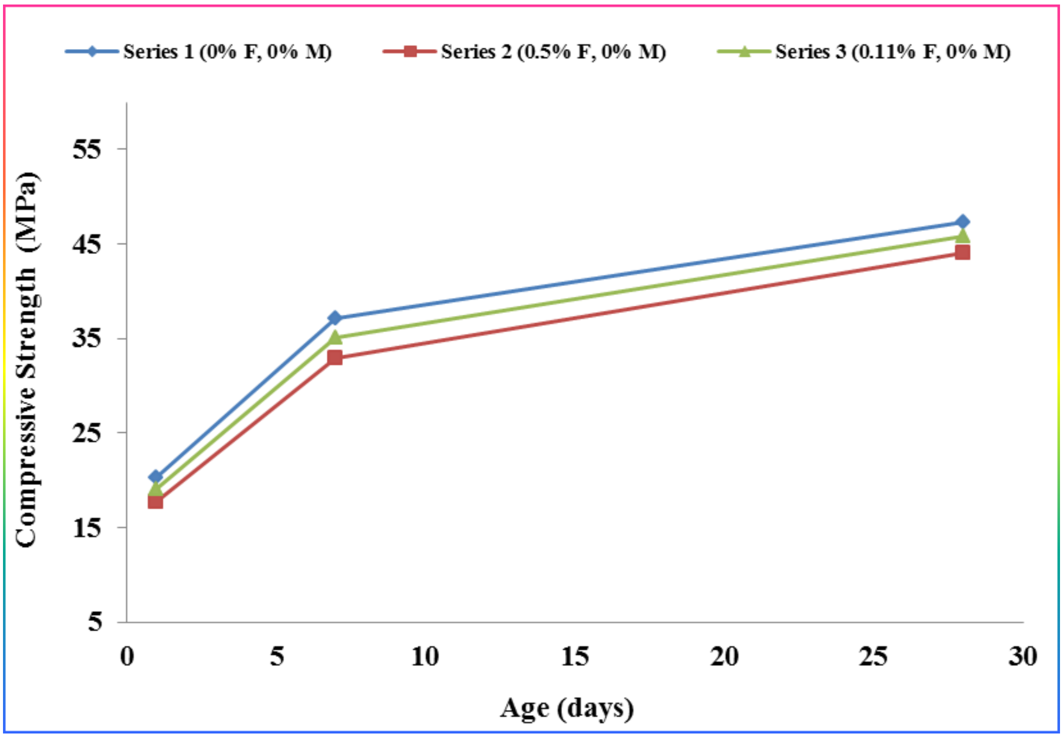


RCA --- Recycled Coarse Aggregate, F --- Fibre, M --- Microsilica

Figure 28. Compressive cube strength at 25%recycled coarse aggregate content

This implies that the incorporation of 54mm Forta-Ferro synthetic macro fibre does not have any significant impact on the compressive cube strength of concrete owing to the fact that the 28-day compressive strength in Series 2 and 3 produced relative strength reduction of about 7% and 3% respectively with reference to Series 1 concrete mix (control mix). Past researchers (Ramakrishnan et al. (1987); Surendra et al. (1978); Zollo (1984)) also corroborate this findings.

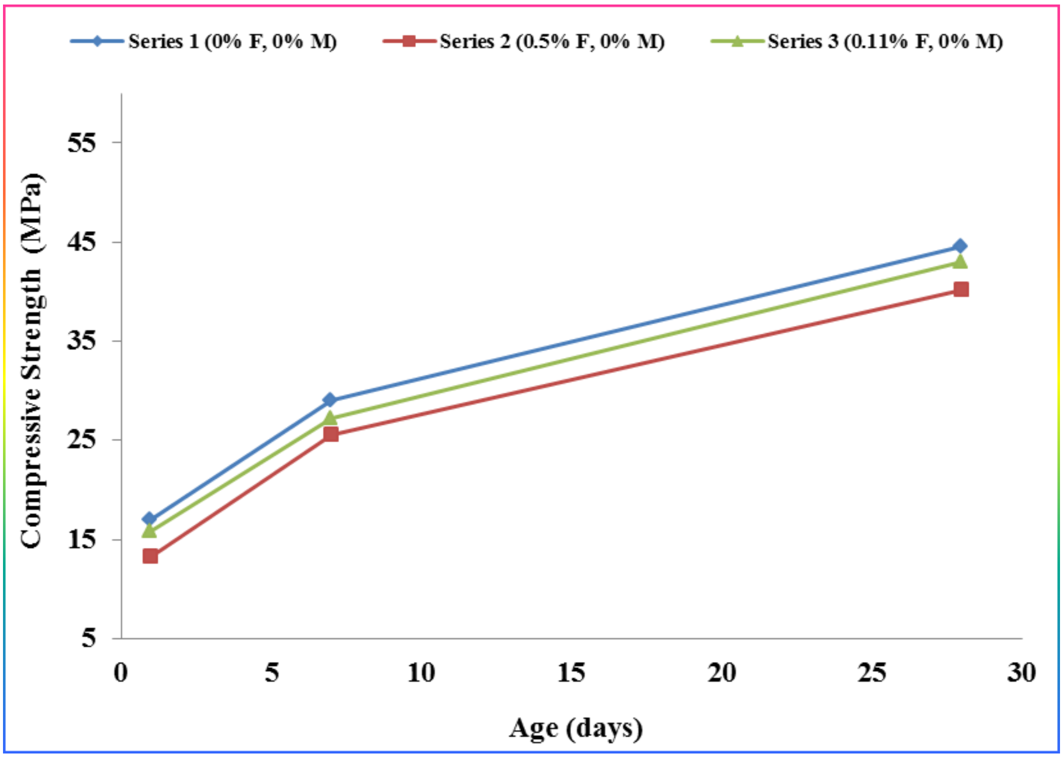
The results of the impact of replacing natural coarse aggregate with 25% recycled coarse aggregate is illustrated in figure 28. The results indicated a less significant reduction in strength for Series 1, 2, and 3 respectively in comparison with results obtained with 0% recycled coarse aggregate content. However, when the natural coarse aggregate was replaced by 100% recycled coarse aggregate, results illustrated in figure 34 shows that the strength reduction with reference to control concrete in Series 1, 2, and 3 concrete mix were 25.7%, 23.8%, and 24.2% respectively.



RCA --- Recycled Coarse Aggregate, F --- Fibre, M --- Microsilica

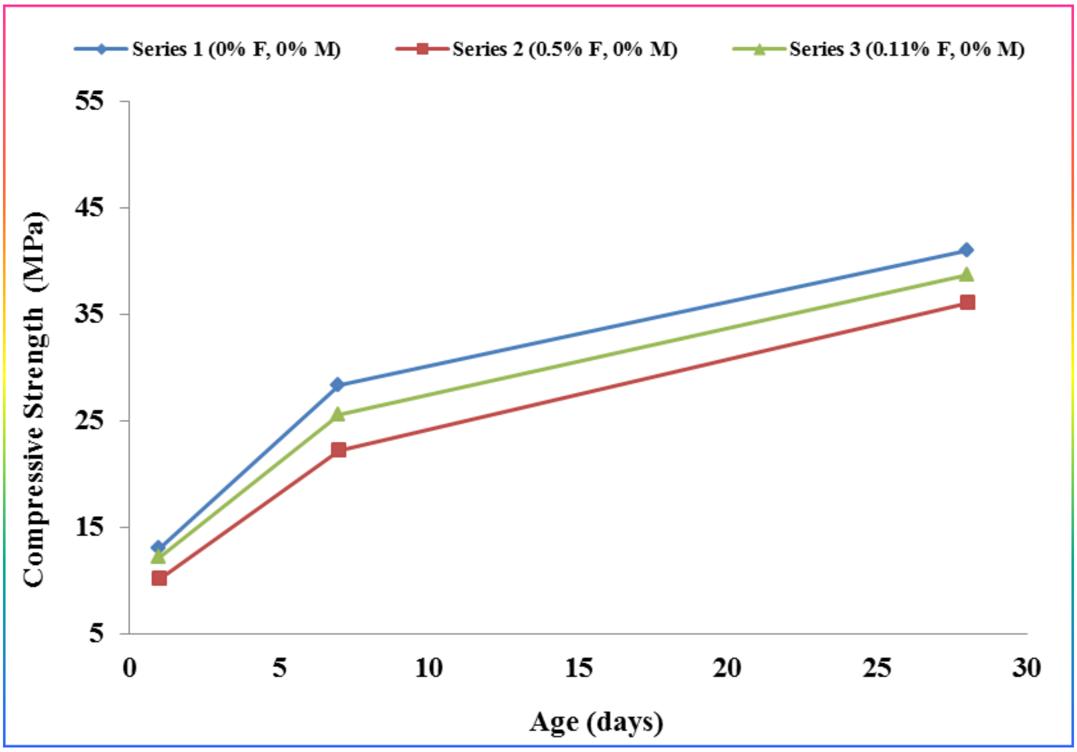
Figure 29. Compressive cube strength at 50% recycled coarse aggregate content

Figures 32 and 33 illustrate the results of compressive cube strength for concrete mixes in Series 1-3 at 50% and 75% recycled coarse aggregate content respectively. The reduction in compressive cube strength of concrete mixes incorporating 50% recycled coarse aggregate with reference to control mixes were 10.4%, 7.9%, and 4.6% respectively for Series 1, 2, and 3 respectively, while the corresponding reduction at 75% recycled coarse aggregate content were 17.3%, 15.1%, and 16% respectively.



RCA --- Recycled Coarse Aggregate, F --- Fibre, M --- Microsilica

Figure 30. Compressive cube strength at 75% recycled coarse aggregate content



RCA --- Recycled Coarse Aggregate, F --- Fibre, M --- Microsilica

Figure 31. Compressive cube strength at 100% recycled coarse aggregate content

Overall, the compressive strength decreases with increasing recycled coarse aggregate (RCA) content in the concrete mix. This is evident in all the concrete mix incorporating recycled coarse aggregate as a substitute for conventional coarse aggregate. Similar observation were reported by several researchers (Frondistou-Yannas, 1977; Hansen, 1986; Hansen and Boegh, 1985; Katz, 2003; Rakshvir and Barai, 2006; Eguchi et al., 2007; Etxeberria, 2007; Domingo-Cabo et al., 2009; Marinković, 2010). Corinaldesi and Moriconi (2009) associated the reduction in compressive strength as recycled coarse aggregate content increased to the presence of weaker aggregate caused by higher porosity of recycled coarse aggregate than conventional coarse aggregate.

Poon et al. (2004), identified about 24% reduction in compressive cube strength of concrete incorporating 100% recycled aggregate. Similar findings were reported by

Adnan et al. (2011) while Kumutha and Vijai (2008) explained that concrete with higher recycled coarse aggregate produced lower compressive strengths when compared with concrete containing less quantity of recycled aggregate. Figures 32 – 36 show various failure patterns of concrete cubes observed during compressive cube strength test.

(a) Series 1 (0% F, 0% M)

(b) Series 2 (0.5% F, 0% M)

(c) Series 3 (0.11% F, 0% M)

Figure 32. Failure patterns of cube specimens at 28-day compression test (0% RCA)

(a) Series 1 (0% F, 0% M)

(b) Series 2 (0.5% F, 0% M)

(c) Series 3 (0.11% F, 0% M)

Figure 33. Failure patterns of cube specimens at 28-day compression test (25% RCA)

(a) Series 1 (0% F, 0% M)

(b) Series 2 (0.5% F, 0% M)

(c) Series 3 (0.11% F, 0% M)

Figure 34. Failure patterns of cube specimens at 28-day compression test (50% RCA)

(a) Series 1 (0% F, 0% M)

(b) Series 2 (0.5% F, 0% M)

(c) Series 3 (0.11% F, 0% M)

Figure 35. Failure patterns of cube specimens at 28-day compression test (75% RCA)

(a) Series 1 (0% F, 0% M)

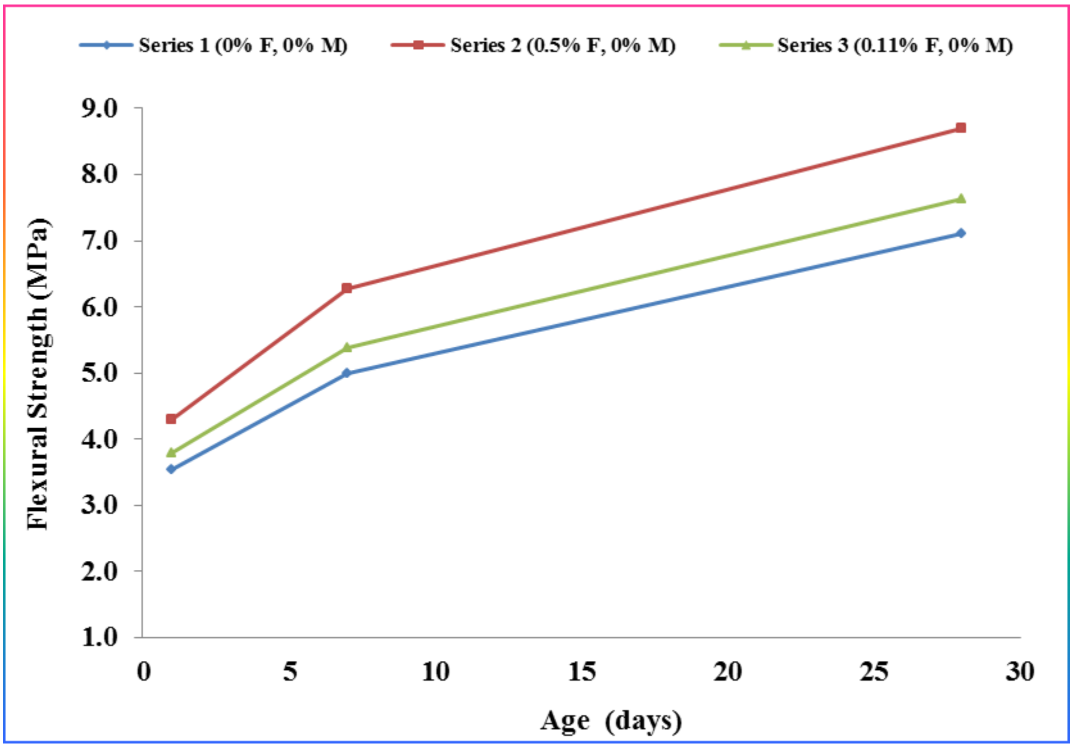
(b) Series 2 (0.5% F, 0% M)

(d) Series 3 (0.11% F, 0% M)

Figure 36. Failure patterns of cube specimens at 28-days compression test (100% RCA)

4.8 Flexural strength test

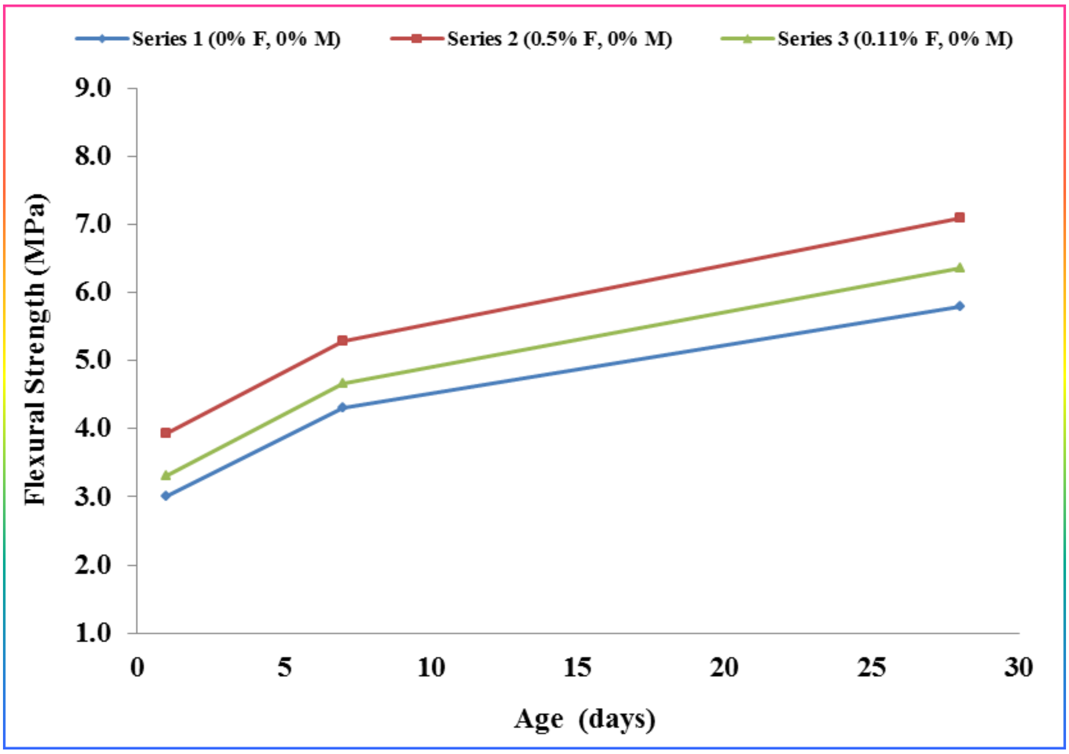
The flexural strength of concrete mixes in Series 1-3 at 1, 7, and 28-day curing age are illustrated in figures 37 - 41 respectively.



RCA --- Recycled Coarse Aggregate, F --- Fibre, M --- Microsilica

Figure 37. Flexural strength at 0% recycled coarse aggregate content

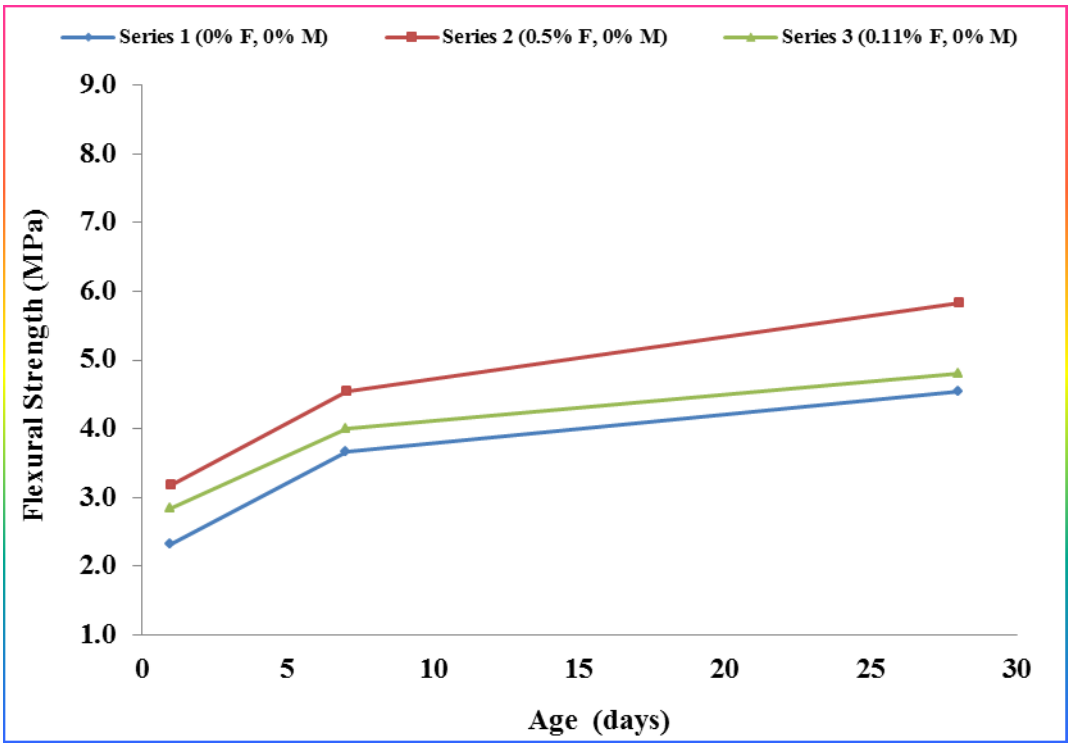
The flexural strength results of concrete mixes in Series 1 (control) illustrated in figure 50 without any fibre dosage reduced considerably when compared with the corresponding mixes in Series 2 and 3 respectively. Concrete mixes in Series 3 with higher dosage rate of synthetic macro fibre produced better result than concrete mixes in Series 2 with lower fibre dosage rate. However, with reference to the control mix in Series 1, concrete mixes in Series 2 and 3 improved the flexural strength more due to the bridging capability and ductile behaviour of synthetic macro fibre which minimised the process of initiating cracks prior to failure.



RCA --- Recycled Coarse Aggregate, F --- Fibre, M --- Microsilica

Figure 38. Flexural strength at 25% recycled coarse aggregate content

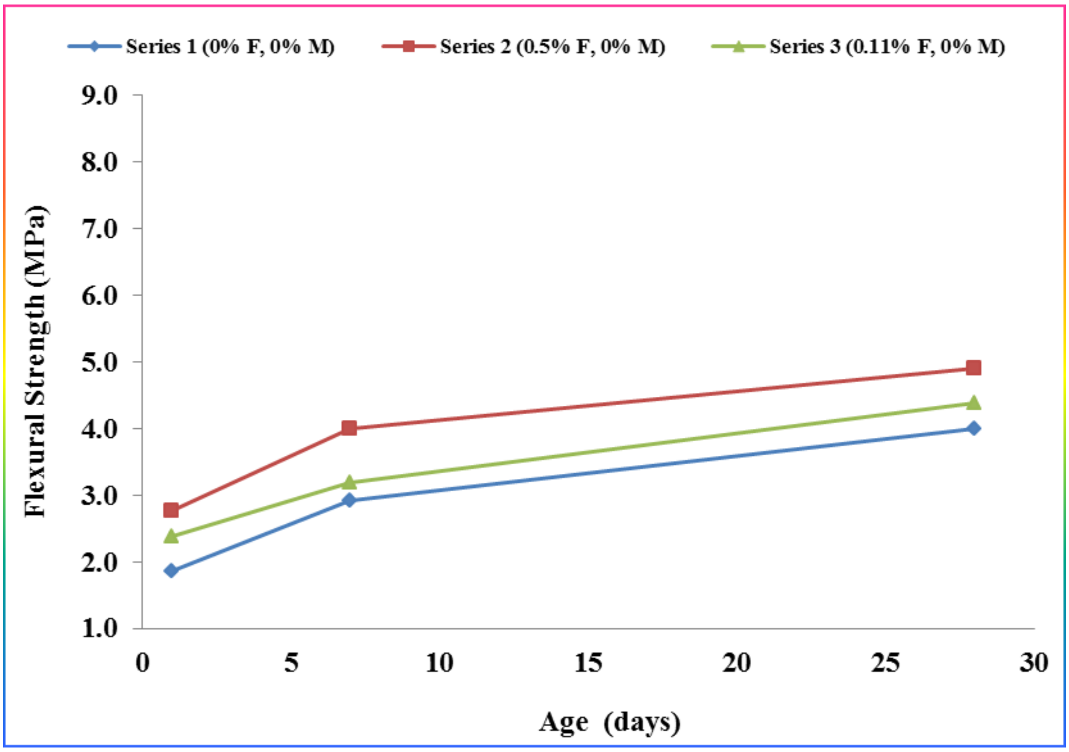
The effect of substitution of natural coarse aggregate with 25% recycled coarse aggregate illustrated in figure 51 above indicate less significant reduction in strength at 28-day curing age with reference to control mix. However, results of flexural strength at 100% recycled coarse aggregate substitution, produced significant reduction of about 51% and 54% at 28-day curing age in Series 2 and 3 respectively. This observation agreed with the findings by Kumutha and Vijai (2008).



RCA --- Recycled Coarse Aggregate, F --- Fibre, M --- Microsilica

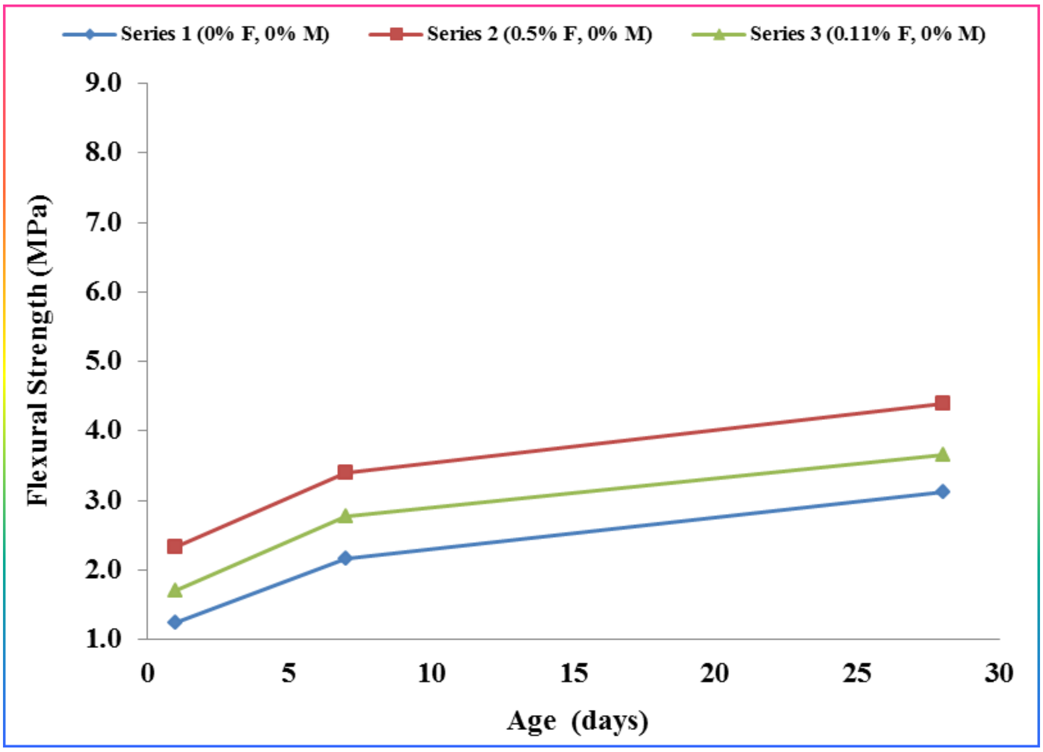
Figure 39. Flexural strength at 50% recycled coarse aggregate content

Similar trend in flexural strength reduction occurred at 50% (figure 39) and 75% (figure 40) recycled aggregate content in concrete mixes in Series 1, 2, and 3 respectively. The relative flexural strength reduction at 50% recycled coarse aggregate content in comparison with the corresponding mixes in Series 1, 2, and 3 (control mix) were 64.2%, 56.8%, and 63.6% respectively while these reductions at 75% substitution were 71.7%, 57.4%, and 70% respectively.



RCA --- Recycled Coarse Aggregate, F --- Fibre, M --- Microsilica

Figure 40. Flexural strength at 75% recycled coarse aggregate content



RCA --- Recycled Coarse Aggregate, F --- Fibre, M --- Microsilica

Figure 41. Flexural strength at 100% recycled coarse aggregate content

Bagherzadeh et al. (2012b), recorded significant increase in flexural strength of concrete incorporating fibre and attributed the result to the ability of fibre to accommodate ductility on the specimen before failure occurred. Generally, the flexural strength shows a reduction with increasing percentage content of recycled coarse aggregate. Various patterns of failure of concrete prisms identified during flexural strength test are shown in figures 42.

(a) Series 1 (0% F, 0% M)

(b) Series 2 (0.5% F, 0% M)

(c) Series 2 (0.5% F, 0% M)

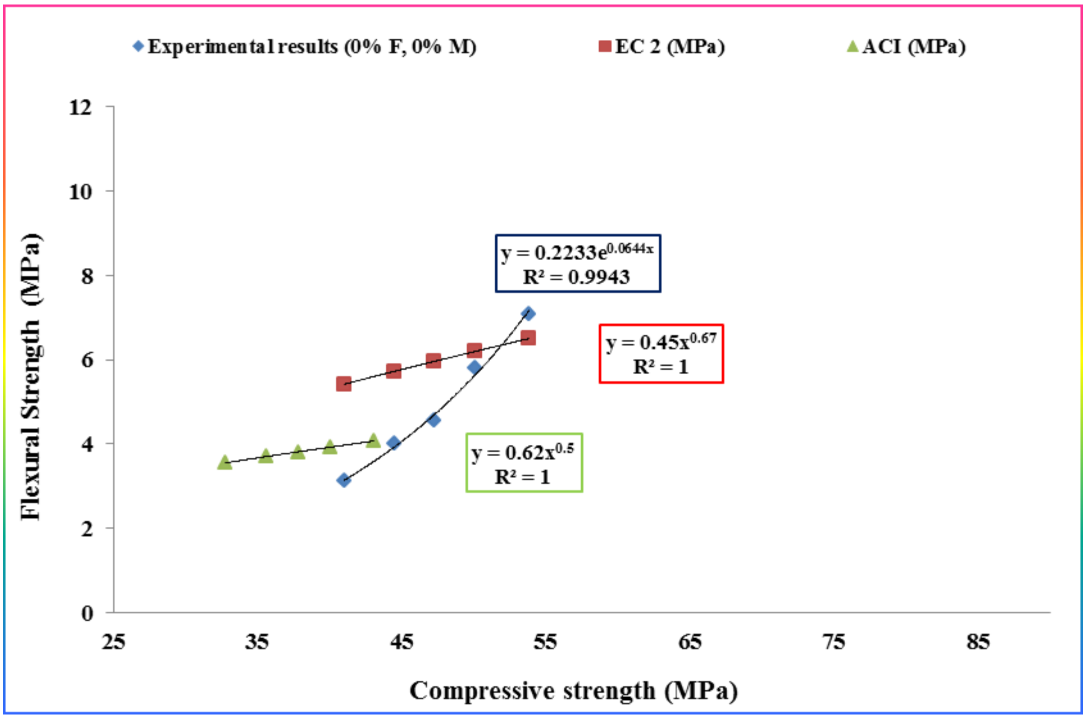
Figure 42. Failure patterns of prism specimens at 28-days flexural test (100% RCA)

4.9 Correlations between Flexural strength and compressive strength

The comparison of actual results of compressive and flexural strength obtained from the experiment against the empirical values obtained from predictive equations given in EC-2 and ACI-318M are given in Table 22 and Figure 43 respectively.

Table 22: Experimental and predictive flexural strength -Series 1 (0% F, 0% M)

RCA (%)	Experimental Compressive strength		Predicted Flexural strength		Experimental Flexural strength (MPa)
	fck, cube (MPa)	fck, cyl. (MPa)	EC 2 (MPa) $\{f_{ct,fl} = 0.45f_{ck}^{(2/3)}\}$	ACI (MPa) $\{f_r = 0.62\sqrt{fck'}\}$	
0	53.86	43.09	6.50	4.07	7.10
25	50.06	40.05	6.19	3.92	5.80
50	47.26	37.81	5.96	3.81	4.55
75	44.53	35.62	5.73	3.70	4.00
100	41.00	32.80	5.42	3.55	3.12



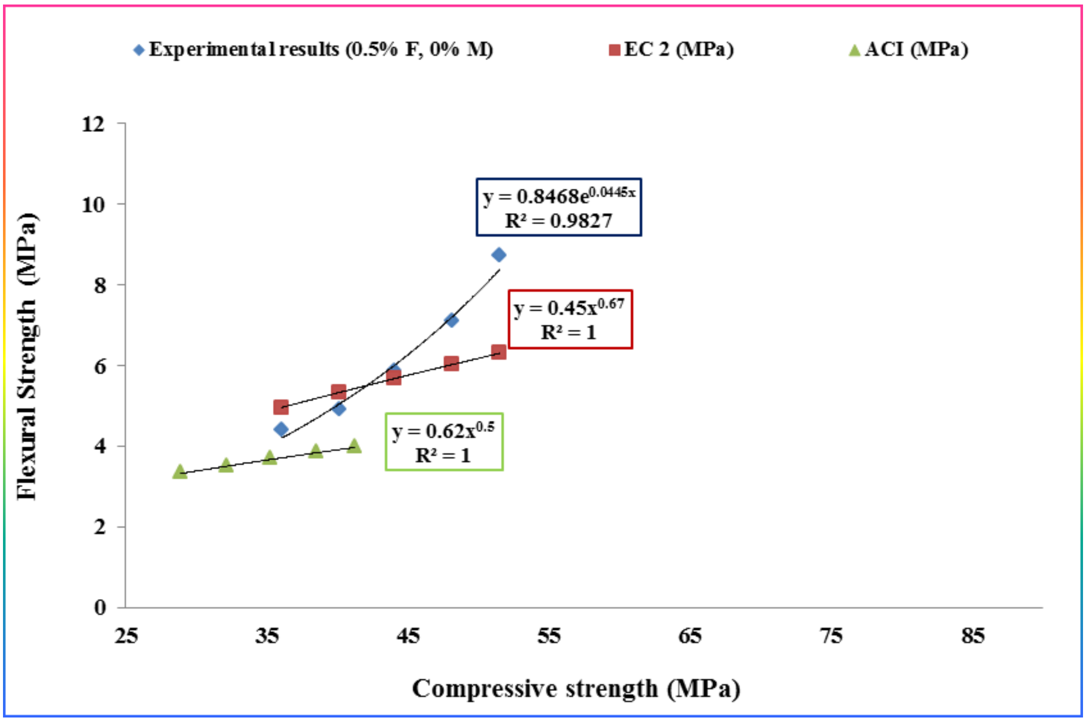
F --- Fibre, M --- Microsilica

Figure 43. Relationship between Flexural strength and compressive strength

It was observed that EC-2 slightly underestimate the flexural strength of concrete mix without recycled coarse aggregate, fibre and microsilica. However, a slight over-estimation was recorded for the mix incorporating 25%, 50%, 75%, and 100% recycled coarse aggregate respectively. On the other hand, ACI slightly underestimate the flexural strength of all the concrete mixes with the exception of the mix incorporating 100% recycled coarse aggregate. The relationship between flexural strength and compressive strength was assessed in order to ascertain the nature of their correlation. Initial assessment indicate that a linear relationship exists between flexural and compressive strength, whereas a close examination indicated an exponential relationship $\mathbf{f_{ct,fl} = 0.22e^{0.06fck}}$ with a correlation coefficient $\mathbf{R^2 = 0.99}$. Table 23 show the result of comparison of compressive and flexural strength obtained from the experiment against the empirical values obtained from predictive equations given in EC-2 and ACI-318M, while Figure 46 depicts the relationship between flexural and compressive strength as exponential $\mathbf{f_{ct,fl} = 0.85e^{0.04fck}}$ with a correlation coefficient $\mathbf{R^2 = 0.98}$.

Table 23: Experimental and predictive flexural strength-Series 2 (0.5% F, 0% M)

RCA (%)	Experimental Compressive strength		Predicted Flexural strength		Experimental Flexural strength (MPa)
	fck, cube (MPa)	fck, cyl. (MPa)	EC 2 (MPa) $\{f_{ct,fl} = 0.45f_{ck}^{(2/3)}\}$	ACI (MPa) $\{f_r = 0.62\sqrt{fck'}\}$	
0	51.53	41.22	6.31	3.98	8.70
25	48.13	38.50	6.03	3.85	7.10
50	44.10	35.28	5.69	3.68	5.84
75	40.20	32.16	5.35	3.52	4.91
100	36.10	28.88	4.97	3.33	4.40



F --- Fibre, M --- Microsilica

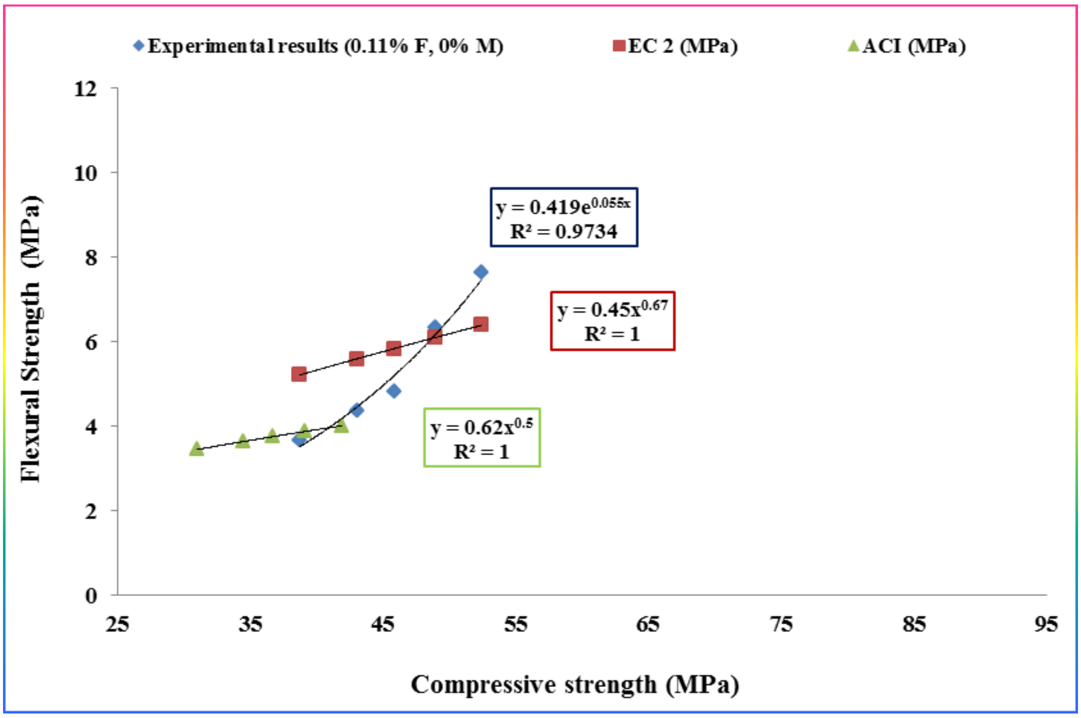
Figure 44. Relationship between Flexural strength and compressive strength

It was observed that EC-2 underestimate the flexural strength of concrete mix with 0%, 25%, and 50% recycled coarse aggregate respectively while concrete mix with 75% and 100% recycled aggregate content were overestimated respectively. ACI significantly underestimate all the flexural strength of concrete mixes in Series 2.

Results from Table 23 show that, the experimental flexural strength of concrete mixes with 0% and 25% recycled aggregate are higher than the predictive value obtained from EC-2 while the flexural strength of mixes with 50%, 75%, and 100% recycled aggregate were overestimated by EC-2 respectively. Predictive equation from ACI significantly underestimate the flexural strength of all the mixes in Series 3. The relationship between flexural and compressive strength assume an exponential relationship $\mathbf{f_{ct,fl} = 0.42e^{0.06fck}}$ with a correlation coefficient $\mathbf{R^2 = 0.97}$.

Table 24: Experimental and predictive flexural strength-Series 3 (0.11% F, 0% M)

RCA (%)	Experimental Compressive strength		Predicted Flexural strength		Experimental Flexural strength (MPa)
	fck, cube (MPa)	fck, cyl. (MPa)	EC 2 (MPa) $\{f_{ct,fl} = 0.45f_{ck}^{(2/3)}\}$	ACI (MPa) $\{f_r = 0.62\sqrt{fck'}\}$	
0	52.40	41.92	6.39	4.01	7.63
25	48.90	39.12	6.10	3.88	6.35
50	45.80	36.64	5.83	3.75	4.81
75	43.00	34.40	5.59	3.64	4.38
100	38.70	30.96	5.21	3.45	3.66

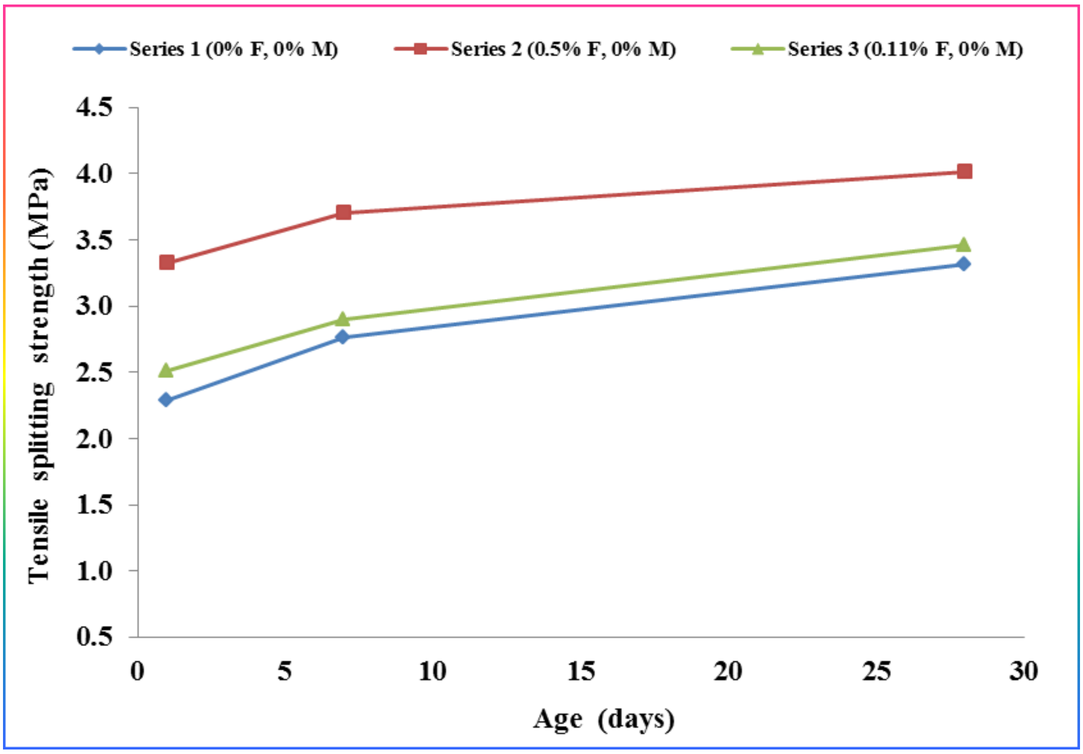


F --- Fibre, M --- Microsilica

Figure 45. Relationship between Flexural strength and compressive strength

4.10 Tensile splitting strength test

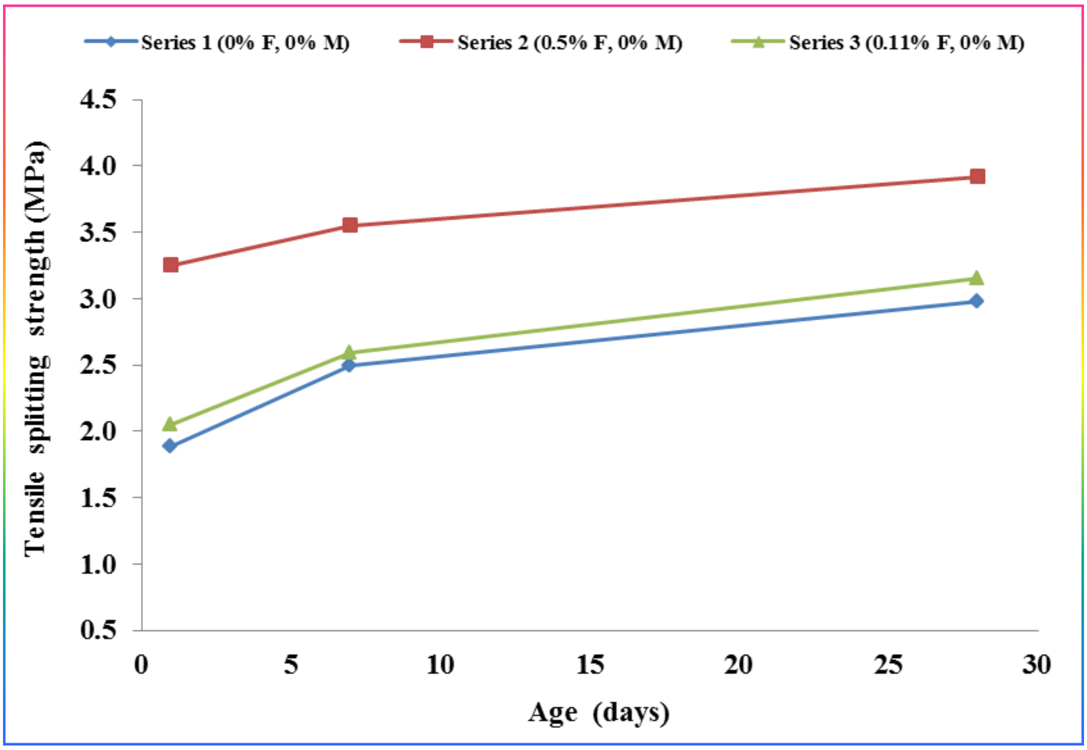
Results of average indirect tensile splitting strength at 1, 7, and 28-day curing age for Series 1, 2, and 3 concrete mixes are illustrated in figures 46-50 respectively.



RCA --- Recycled Coarse Aggregate, F --- Fibre, M --- Microsilica

Figure 46. Tensile splitting strength at 0% recycled coarse aggregate content

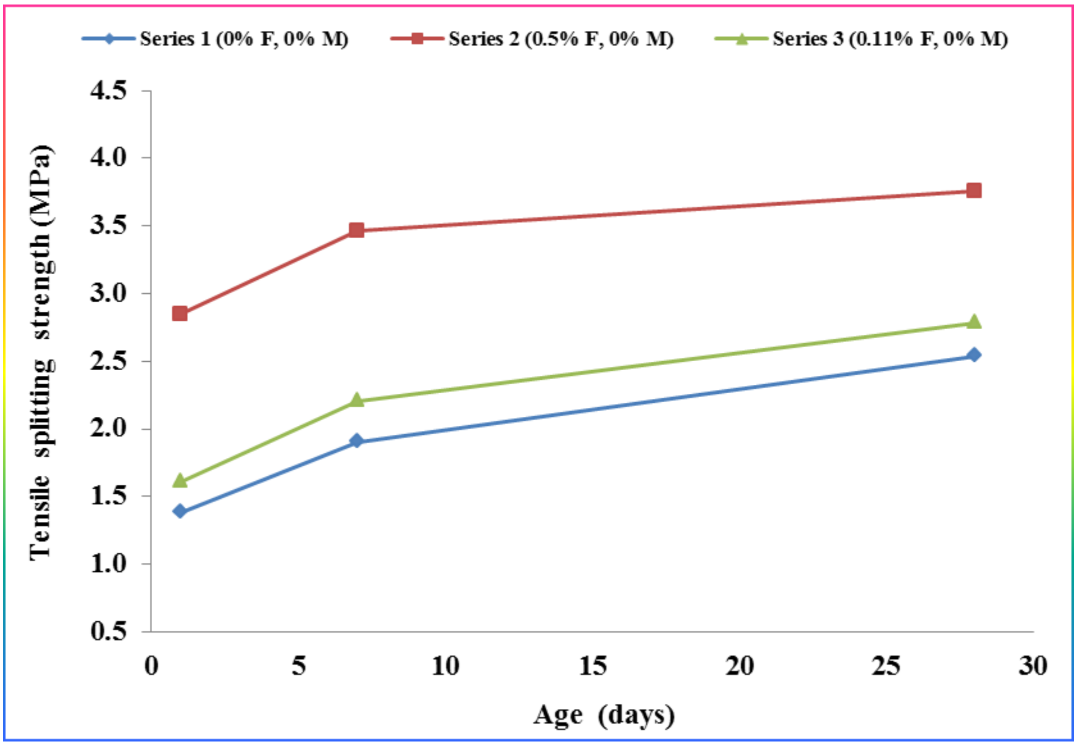
Results of tensile splitting strength from figure 58 above indicate that concrete mixes in Series 2 with higher synthetic macro fibre dosage produced better results than concrete mixes in Series 1 and 3 respectively. The 28-day relative strength of Series 2 concrete mix were 15.9% and 20.8% of the corresponding mixes in Series 1 and 3 respectively.



RCA --- Recycled Coarse Aggregate, F --- Fibre, M --- Microsilica

Figure 47. Tensile splitting strength at 25% recycled coarse aggregate content

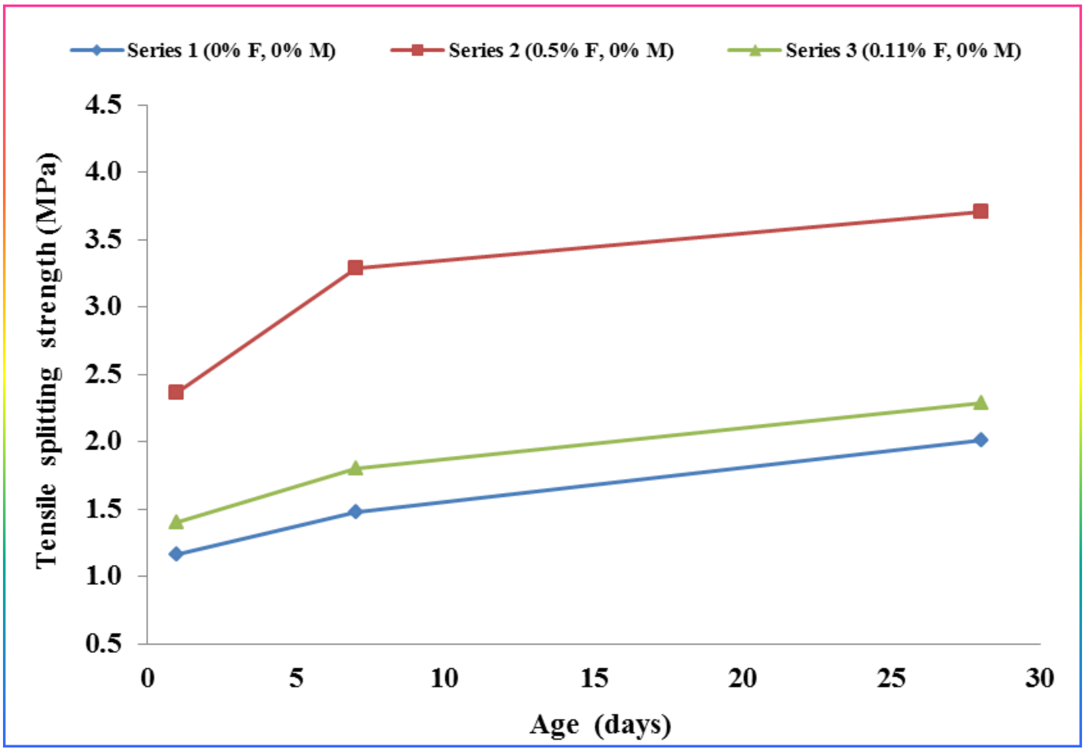
Figure 47 illustrates the tensile spliting strength results of concrete mix in Series 1,2, and 3 respectively with 25% recycled coarse aggregate content. The plots shows that Series 2 concrete mix at 28-day curing age had tensile splitting strength of about 31.5% and 24.4% more than the corresponding mix in Series 1 and 3 respectively. However, the Series 2 concrete mix which incorporates lower dosage of synthetic macro fibre, gained about 5.7% more tensile splitting strength than Series 1 mix at 28-day uring age . This was due to the incorporation of smaller volume of fibre in the concrete mix compared with Series 3 concrete mix.



RCA --- Recycled Coarse Aggregate, F --- Fibre, M --- Microsilica

Figure 48. Tensile splitting strength at 50% recycled coarse aggregate content

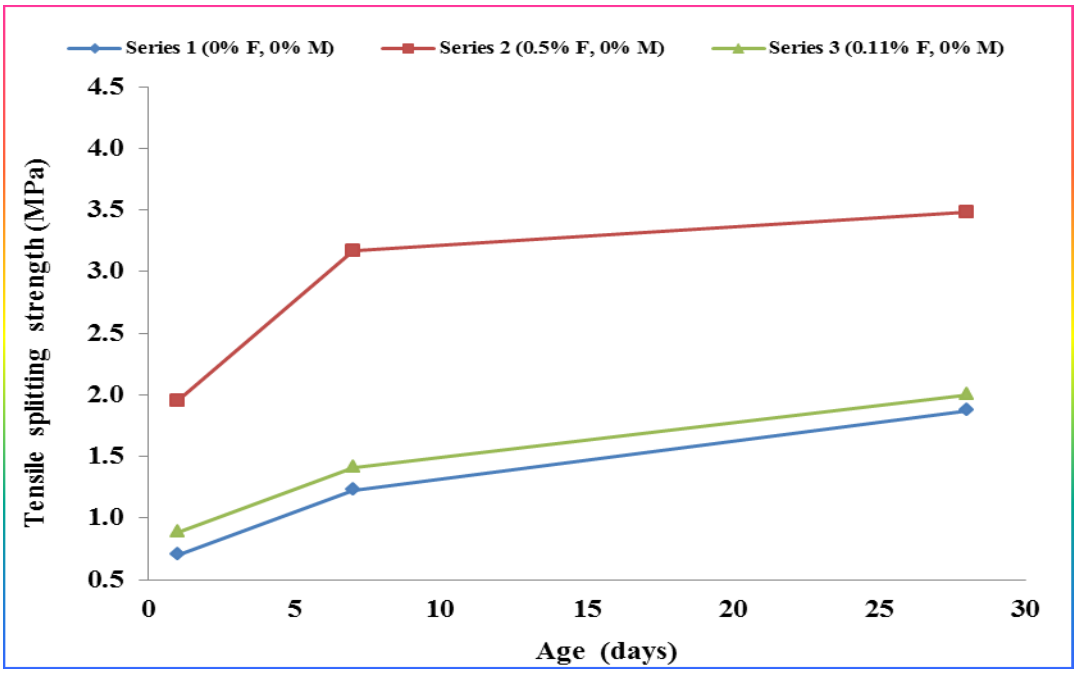
Results of tensile splitting strength of concrete mix incorporating 50% recycled aggregate content is illustrated in figure 48. It was observed that Series 2 concrete mix produced tensile strength result of about 48% and 35% higher than the corresponding mixes in Series 1 and 3 respectively at 28-day curing age, while Series 3 had about 9.4% more tensile strength than Series 1 mix. These results imply that the effect of increasing recycled coarse aggregate content is obvious compared with relative strength difference in figure 53.



RCA --- Recycled Coarse Aggregate, F --- Fibre, M --- Microsilica

Figure 49. Tensile splitting strength at 75% recycled coarse aggregate content

Figure 49 illustrates the results of tensile spliting strength for concrete mix in Series 1,2, and 3 respectively with 75% recycled coarse aggregate content. Series 2 concrete mix at 28-day curing age had tensile splitting strength of about 84.5% and 62% more than the corresponding mix in Series 1 and 3 respectively. The results reflects the impact of increasing recycled coarse aggregate in the concrete mix and the influence of synthetic macro fibre addition.



RCA --- Recycled Coarse Aggregate, F --- Fibre, M --- Microsilica

Figure 50. Tensile splitting strength at 100% recycled coarse aggregate content

The tensile splitting strength results for concrete mix in Series 1, 2, and 3 at 1, 7, and 28-day curing age is illustrated in figure 50 above. The relative increase in tensile splitting strength in Series 2 compared to corresponding concrete mix in Series 1 and 3 respectively at 28-day were 86.1% and 69.8% respectively. This indicate a wide disparity at 100% recycled coarse aggregate content.

Generally, the results show that tensile splitting strength decreased with increase in percentage content of recycle aggregate. This observation corroborates the strength reduction pattern reported by Evangelista and De Brito (2007) which was attributed to the porous nature of the recycled aggregate. The incorporation of higher dosage of synthetic macro fibre improved the 28-day tensile splitting strength of concrete mixes in Series 2 at different percentage substitution of recycled coarse aggregate with reference to the corresponding concrete mix in Series 1. This increase in Series 2 concrete mixes was due to the bridging capability of fibre in absorbing energy in the concrete thereby reducing the tendency of early cracks initiation. The disparity between Series 2 and other Series was significant under tensile splitting strength test compared with flexural strength test. This trend agreed with reported findings by Bagherzadeh et al. (2012b). Various failure patterns of concrete cylinders obtained from tensile splitting test are displayed in figures 63-66.

(a) Series 1 (0% F, 0% M)

(b) Series 2 (0.5% F, 0% M)

(c) Series 3 (0% F, 0% M)

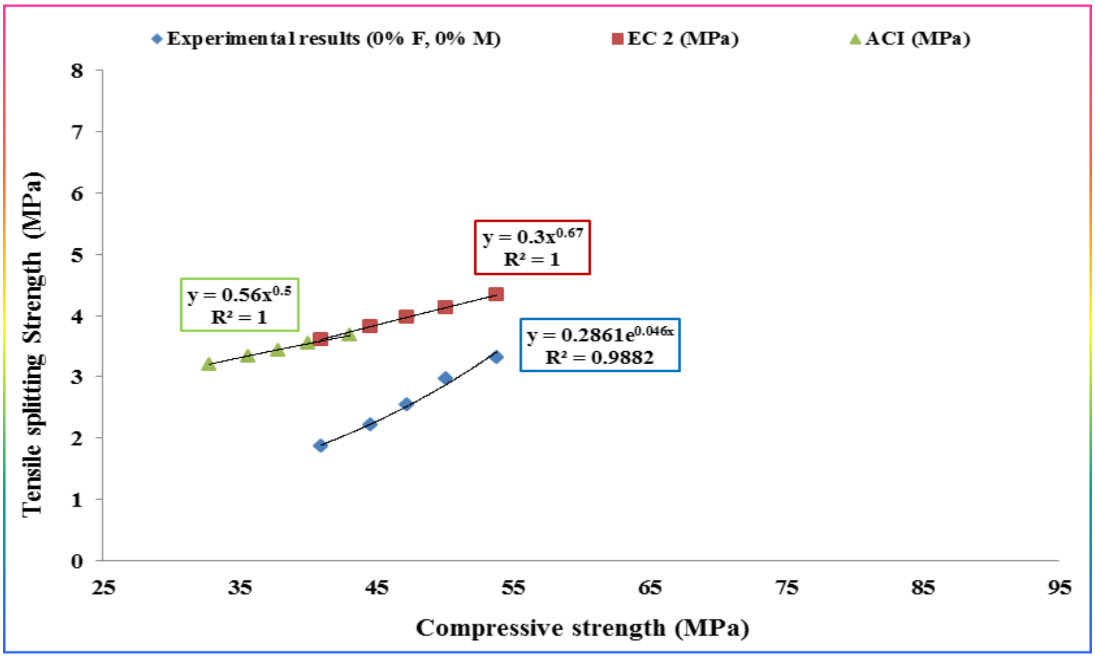
Figure 51. Failure patterns of cylinder specimens at 28-days flexural test (0% RCA)

4.11 Correlations between Tensile splitting strength and compressive strength

The comparison of actual results of compressive and tensile splitting strength obtained from the experiment against the empirical values obtained from predictive equations given in EC-2 and ACI-318M are given in Table 25 and figure 52 respectively.

Table 25: : Experimental and predictive tensile splitting strength -Series 1 (0% F, 0% M)

RCA (%)	Experimental Compressive strength		Predicted Tensile splitting strength		Experimental Tensile splitting strength (MPa)
	fck, cube (MPa)	fck, cyl. (MPa)	EC 2 (MPa) $\{f_{ct,fl} = 0.30 f_{ck}^{(2/3)}\}$	ACI (MPa) $\{f_r = 0.56\sqrt{fck'}\}$	
0	53.86	43.09	4.34	3.68	3.32
25	50.06	40.05	4.13	3.54	2.98
50	47.26	37.81	3.97	3.44	2.54
75	44.53	35.62	3.82	3.34	2.21
100	41.00	32.80	3.61	3.21	1.87



F --- Fibre, M --- Microsilica

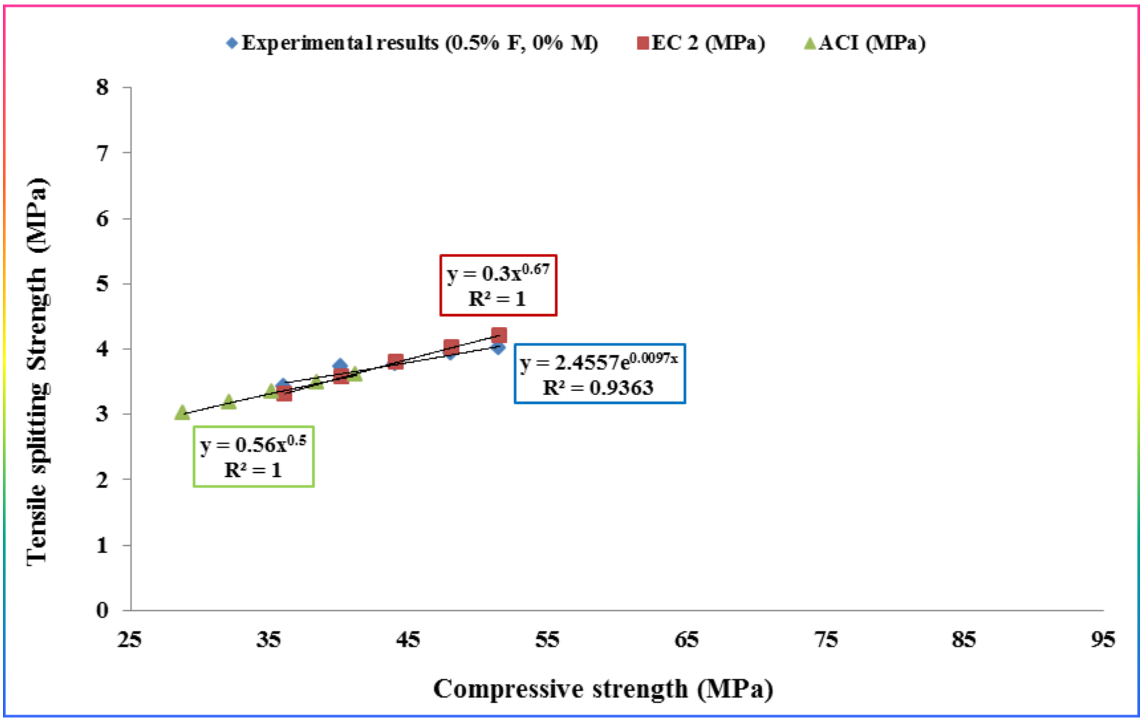
Figure 52. Relationship between Tensile splitting strength and compressive strength

It was observed that EC-2 and ACI slighty overestimate the flexural strength of all the concrete mixes in Series 1 without fibre and microsilica. An exponential relationship $\mathbf{f_{ct,sp} = 0.29e^{0.05fck}}$ with a correlation coefficient $\mathbf{R^2 = 0.99}$ exists between tensile splitting strength and compressive strength.

Table 26 show the result of comparison of compressive and tensile splitting strength obtained from the experiment against the empirical values obtained from predictive equations given in EC-2 and ACI-318M, while Figure 53 depicts the relationship as exponential $\mathbf{f_{ct,sp} = 2.46e^{0.01fck}}$ with a correlation coefficient $\mathbf{R^2 = 0.94}$

Table 26: Experimental and predictive tensile splitting strength -Series 2(0.5% F, 0% M)

RCA (%)	Experimental Compressive strength		Predicted Tensile splitting strength		Experimental Tensile splitting strength (MPa)
	fck, cube (MPa)	fck, cyl. (MPa)	EC 2 (MPa) $\{f_{ct,sp} = 0.45f_{ck}^{(2/3)}\}$	ACI (MPa) $\{f_r = 0.62\sqrt{fck'}\}$	
0	51.53	41.22	4.21	3.60	4.01
25	48.13	38.50	4.02	3.47	3.92
50	44.10	35.28	3.79	3.33	3.76
75	40.20	32.16	3.56	3.18	3.71
100	36.10	28.88	3.32	3.01	3.42



F --- Fibre, M --- Microsilica

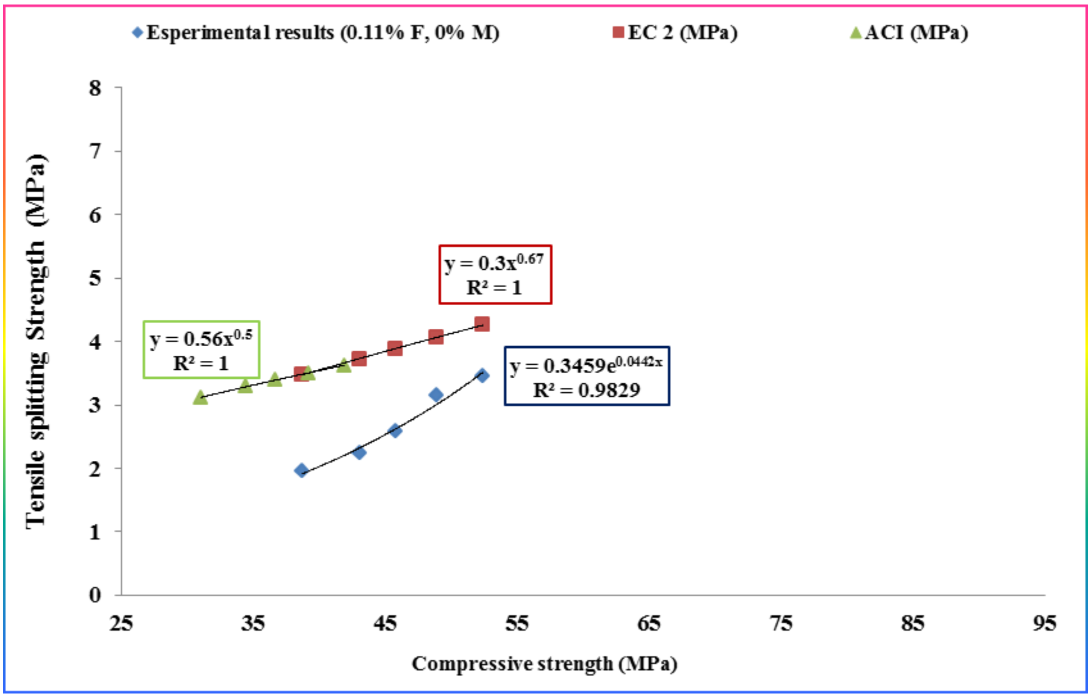
Figure 53. Relationship between Tensile splitting strength and compressive strength

EC-2 overestimate the tensile splitting strength of concrete mixes in Series 2 with 0%, 25%, and 50% recycled coarse aggregate content respectively while mixes with 75% and 100% recycled aggregate content were underestimared. On the other hand, ACI underestimate the tensile splitting strength of all the concrete mixes in Series 2.

Table 27 show the result of comparison of compressive and tensile splitting strength obtained from the experiment against the empirical values obtained from predictive equations given in EC-2 and ACI-318M, while Figure 54 depicts the relationship as exponential $\mathbf{f_{ct,sp} = 0.35e^{0.04fck}}$ with a correlation coefficient $\mathbf{R^2 = 0.98}$. It was observed that both EC-2 and ACI overestimate the flexural strength of all the concrete mixes in Series 3.

Table 27: Experimental and predictive tensile splitting strength-Series 3(0.11% F, 0% M)

RCA (%)	Experimental Compressive strength		Predicted Flexural strength		Experimental Flexural strength (MPa)
	fck, cube (MPa)	fck, cyl. (MPa)	EC 2 (MPa) $\{f_{ct,fl} = 0.45f_{ck}^{(2/3)}\}$	ACI (MPa) $\{f_r = 0.62\sqrt{fck'}\}$	
0	52.40	41.92	4.26	3.63	3.46
25	48.90	39.12	4.06	3.50	3.15
50	45.80	36.64	3.89	3.39	2.58
75	43.00	34.40	3.73	3.28	2.25
100	38.70	30.96	3.47	3.12	1.95



F --- Fibre, M --- Microsilica

Figure 54. Relationship between Tensile splitting strength and compressive strength

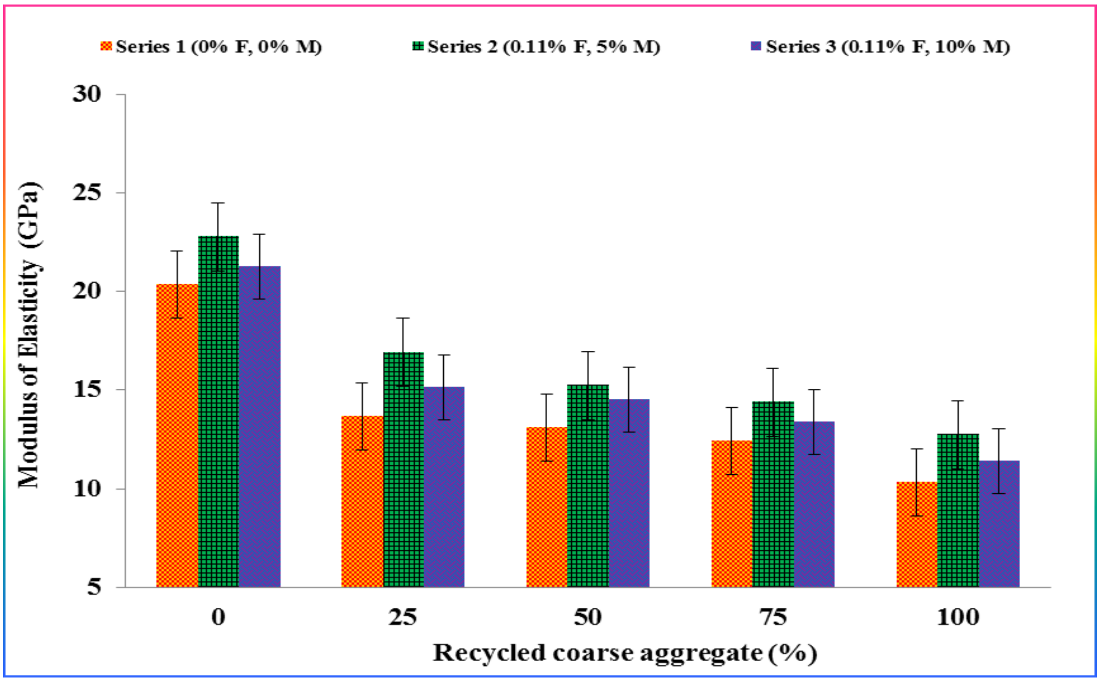
4.12 Static Modulus of Elasticity

Results of 28-day static modulus of elasticity for concrete mixes in Series 1-3 are given in Table 28 and are illustrated in Figure 65 respectively.

Table 28: Result of 28-day static modulus of elasticity

RCA (%)	Series 1 (0% Fibre, 0% Micro silica)	Series 2 (0.5% Fibre, 0% Micro silica)	Series 3 (0.11% Fibre, 0% Micro silica)
0	20.35	22.79	21.27
25	13.66	16.91	15.13
50	13.10	15.25	14.51
75	12.43	14.38	13.37
100	10.33	12.74	11.39

RCA --- Recycled Coarse Aggregate, F --- Fibre, M --- Microsilica



RCA --- Recycled Coarse Aggregate, F --- Fibre, M --- Microsilica

Figure 55. 28-day static modulus of elasticity

Results in Series 2 and 3 respectively, which incorporate synthetic macro fibre, indicate more improvement in elastic modulus of concrete compared with corresponding mix in Series 1 at various recycled coarse aggregate content. This implies that synthetic macro fibre played a very important role in enhancing the concrete to absorb more energy which subsequently result in reduction of strain during loading and unloading of the concrete cylinders. Series 2 concrete mix also produced higher results of about 12% and 7.1% more than the corresponding mixes in Series 1 and 3 respectively at 0% recycled coarse aggregate content.

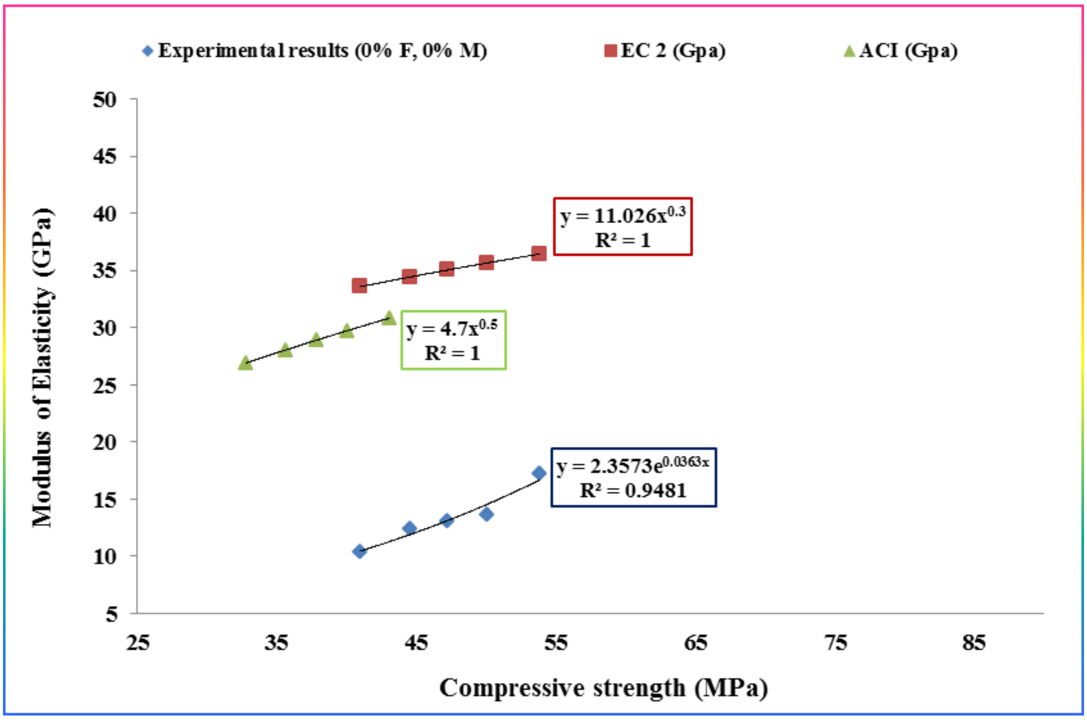
The relative increase in modulus of elasticity of Series 2 concrete mix at 25% recycled coarse aggregate content with reference to Series 1 and 3 were 23.8% and 11.8% respectively. Similarly, the elastic modulus of Series 2 concrete mix at 50% recycled coarse aggregate content relative to Series 1 and 3 concrete mix were 16.4% and 5.1% respectively, while 75% recycled coarse aggregate substitution in Series 2 concrete mix produced 15.7% and 7.8% increase in static modulus of elasticity in comparison with Series 1 and 3 respectively. Elastic modulus of concrete mix in Series 2 were 23.3% and 11.9% more than the elastic modulus recorded for concrete mix in Series 1 and 3 respectively. The overall modulus of elasticity results indicate a decreasing pattern of modulus of elasticity when the recycled coarse aggregate content increased, and this was attributed to the lower modulus of elasticity of recycled coarse aggregate compared to natural coarse aggregate. The elastic modulus of concrete mix containing 100% recycled coarse aggregate reduced significantly with respect to the control concrete mix and these relative reductions were 49.2%, 44.1%, and 46.4% respectively corresponding to Series 1, 2, and 3 respectively. Berndt (2009b), identified a reduction in elastic modulus with increasing replacement of natural coarse aggregate by recycled coarse aggregate. Xiao et al. (2005b) reported reduction of about 45%, while Frondistou-Yannas (1977) suggested approximately 40% decrease in elastic modulus with 100% recycled coarse aggregate content.

4.13 Correlations between static elastic modulus and compressive strength

The comparison of actual results of compressive strength and elastic modulus obtained from the experiment against the empirical values obtained from predictive equations given in EC-2 and ACI-318M are given in Tables 29, 30, and 31, and figures 56, 57, and 58 for Series 1, 2, and 3 conrete mixes respectively.

Table 29: Experimental and predictive modulus of elasticity- Series 1 (0% F, 0% M)

RCA (%)	Experimental Compressive strength		Predicted elastic modulus		Experimental elastic modulus (GPa)
	fck, cube (MPa)	fck, cyl. (MPa)	EC 2 (GPa) $\{E_{cm} = 22[f_{cm}/10]^{0.3}\}$	ACI (GPa) $\{E_c = 4.7(f_c')^{0.5}\}$	
0	53.86	43.09	36.46	30.85	17.25
25	50.06	40.05	35.67	29.74	13.66
50	47.26	37.81	35.06	28.90	13.10
75	44.53	35.62	34.44	28.05	12.43
100	41.00	32.80	33.59	26.92	10.33

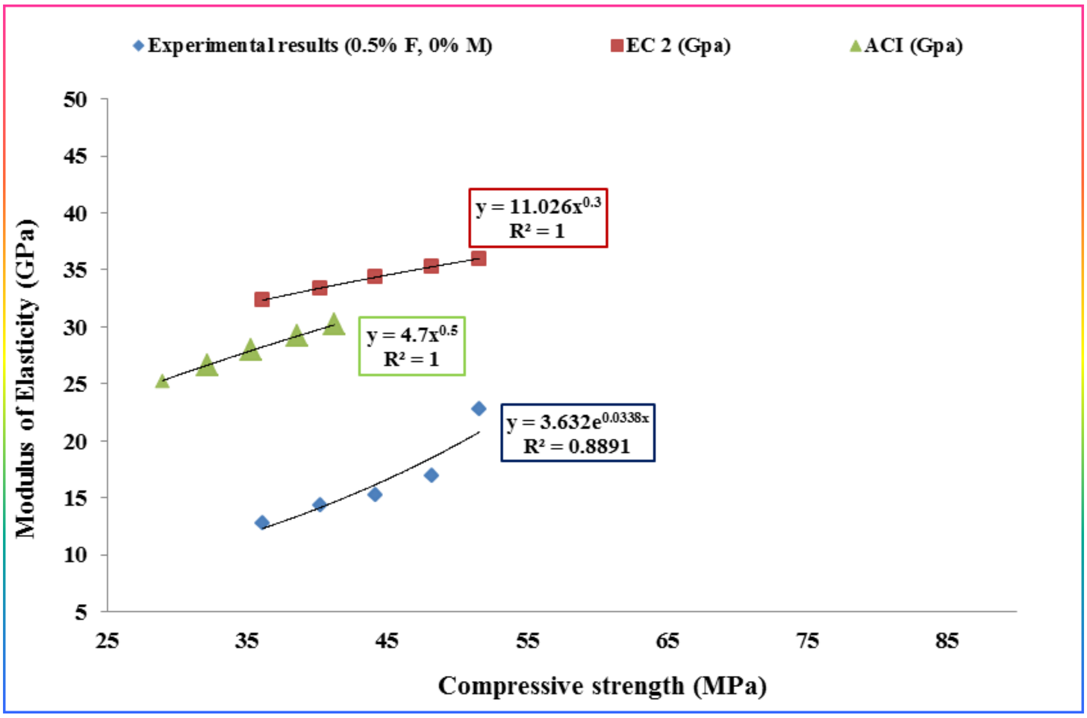


F --- Fibre, M --- Microsilica

Figure 56. Relationship between elastic modulus and compressive strength

Table 30: Experimental and predictive modulus of elasticity -Series 2 (0.5% F, 0% M)

RCA (%)	Experimental Compressive strength		Predicted elastic modulus		Experimental elastic modulus (GPa)
	fck, cube (MPa)	fck, cyl. (MPa)	EC 2 (GPa) $\{E_{cm} = 22\ [f_{cm}/10]^{0.3}\}$	ACI (GPa) $\{ E_c = 4.7(f_c')^{0.5}\}$	
0	51.53	41.22	35.98	30.18	22.79
25	48.13	38.50	35.25	29.16	16.91
50	44.10	35.28	34.34	27.92	15.25
75	40.20	32.16	33.40	26.65	14.38
100	36.10	28.88	32.34	25.26	12.74

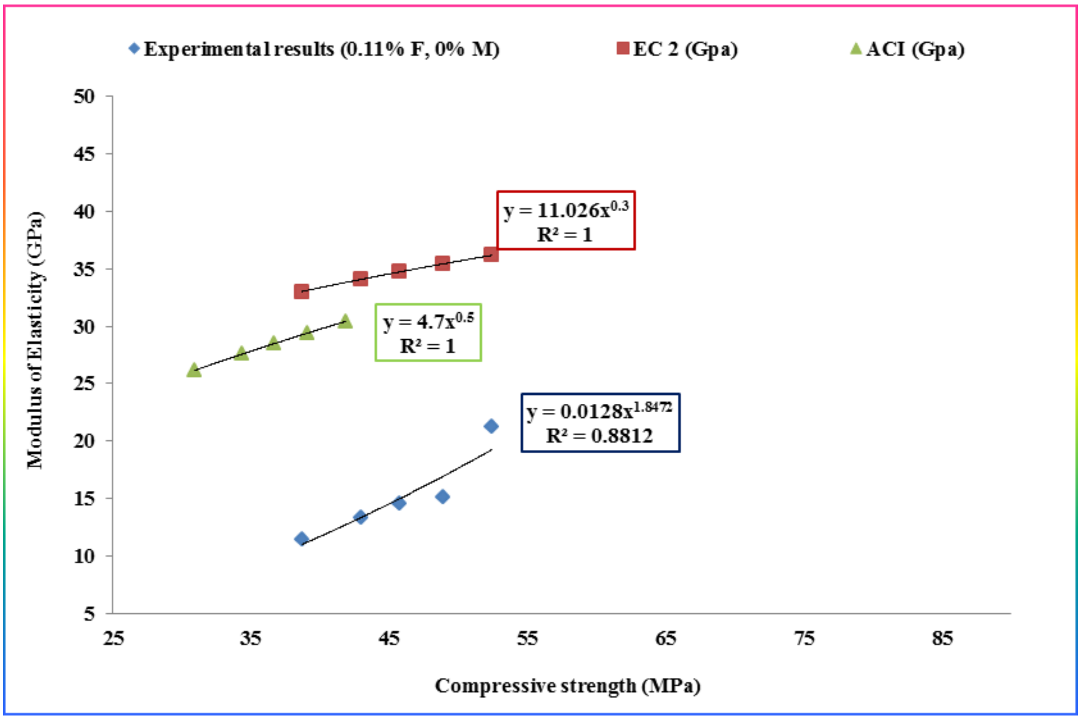


F --- Fibre, M --- Microsilica

Figure 57. Relationship between elastic modulus and compressive strength

Table 31: Experimental and predictive modulus of elasticity-Series 3 (0.11% F, 0% M)

RCA (%)	Experimental Compressive strength		Predicted elastic modulus		Experimental elastic modulus (GPa)
	fck, cube (MPa)	fck, cyl. (MPa)	EC 2 (GPa) $\{E_{cm} = 22\ [f_{cm}/10]^{0.3}\}$	ACI (GPa) $\{E_c = 4.7(f_c')^{0.5}\}$	
0	52.40	41.92	36.16	30.43	21.27
25	48.90	39.12	35.42	29.40	15.13
50	45.80	36.64	34.73	28.45	14.51
75	43.00	34.40	34.08	27.57	13.37
100	38.70	30.96	33.02	26.15	11.39



F --- Fibre, M --- Microsilica

Figure 58. Flexural strength at 75% recycled coarse aggregate content

It was observed that the results obtained from the experiment were lower than the values obtained from the empirical equations. EC-2 and ACI significantly overestimate the modulus of elasticity of all the concrete mixes in Series 1and these values doubles the actual values obtained experimentally. These differences can be linked to the empirical nature of the predictive equations. The equations were based on normal strength concrete without recycled aggregate and fibre inclusion and therefore it is very unlikely that the predictions will be suitable for recycled aggregate concrete incorporating fibre and microsilica. Since the elastic modulus of concrete is a function of the aggregate, cement paste and other constituents, it is expected that the substitution of natural coarse aggregate with recycled coarse aggregate will have impact on the elastic modulus of concrete made from such composition.

The relationship between modulus of elasticity and compressive strength followed a power regression equation as shown in figures 56, 57, and 58.

The following equations obtained from the regression analysis and their respective coefficient of correlation can be used to predict elastic modulus of concrete for Series1, 2, and 3 concrete mixes respectively.

$E_c = 0.02fck^{1.7}$ ($R^2 = 0.94$) ------------------ Series 1 (0% Fibre, 0% Microsilica)

$E_c = 0.07fck^{1.4}$ ($R^2 = 0.86$) ----------------- Series 2 (0.5% Fibre, 0% Microsilica)

$E_c = 0.01fck^{1.8}$ ($R^2 = 0.88$) ----------------- Series 3 (0.11% Fibre, 0% Microsilica)

4.14 Summary of findings

The conclusions from this experimental work are;

1) Recycled coarse aggregate has higher water absorption rate and lower particle density than natural coarse aggregate;
2) Results from the particle size distribution (Sieving method) show that natural fine aggregate, natural coarse aggregate and recycled coarse aggregate used in this research work are within the acceptable limits for concrete according to BS-EN-12620:2013.
3) There were significant reductions in physical and mechanical characteristics of fibre reinforced recycled aggregate concrete as percentage content of recycled coarse aggregate increased;
4) The incorporation of synthetic macro fibre had little or no significant impact on compressive strength of recycled aggregate concrete in all the mixes in Series 1-3 but led to a marked increase flexural strength, tensile splitting strength and static modulus of elasticity respectively;

5) The modulus of elasticity of the mixes in Series 1-3 fall below the theoretical value of 35 GPa given in Table 3.1 of BS-EN 1992-1-1:2004 for 28-day characterstics compressive cube strength of 50MPa .

5 EFFECT OF MICROSILICA AND SYNTHETIC MACRO FIBRE ON RECYCLED AGGREGATE CONCRETE

5.1 Introduction

This chapter describes details of another objective of this research work which is to evaluate the effect of addition of mineral admixture (microsilica) on both physical and engineering properties of fibre reinforced concrete produced in Phase one of the laboratory experiments already discussed in chapter four. After Phase one experiments, Phase two concrete mix design also followed the conventional UK mix design method (BRE, 1997), 'design of normal concrete mix manual'. It consists of five concrete batches incorporating 5% microsilica as an addition to cement and due to the observation from Phase one with respect to the insignificant impact of 54mm synthetic macro fibre dosage on compressive strength, the mix under Phase two only incorporates 1kg/m³ (0.11%) synthetic macro fibre as shown in Table 32.

Table 32: Concrete mix details – series 4 (0.11% Fibre, 5% microsilica)

Recycle Aggregate by weight of coarse aggregate. (%)	0	25	50	75	100
Cement (kg/m³)	583	583	583	583	583
Sand (kg/m³)	603	603	603	603	603
Gravel (kg/m³)	904	678	452	226	0
RCA. (kg/m³)	0	226	452	678	904
Water (kg/m³)	230	230	230	230	230
Synthetic Macro Fibre - 0.11% by volume of concrete (kg/m³)	1	1	1	1	1
Microsilica (kg/m³) - 5% by weight of cement	29.2	29.2	29.2	29.2	29.2
Superplasticiser by weight of cement (kg/m³)	2.33	2.33	2.33	3.50	3.50

RCA --- Recycled Coarse Aggregate, F --- Fibre, M --- Microsilica

The percentage substitution of natural coarse aggregate by recycled coarse aggregate in the concrete mix and other specified parameters such as the 28-day characteristics compressive cube strength, target mean compressive cube strength, workability and free-water/cement ratio remain the same as in Phase one. In order to maintain a similar consistency level as specified in the design mix, a high range superplasticiser (Alphaflow 420), which is a modified synthetic carboxylated polymer was selected as chemical admixture. The superplasticiser was mixed with water at various percentage on trial and error basis until two percentages (0.4% and 0.6%) by weight of cement were established according to the percentage replacement of natural aggregate by recycled coarse aggregate.

The objective of phase two experiment was to compare the results obtained against the results already recorded in chapter 4 in order to evaluate the effect of microsilica addition on fibre reinforced concrete with partial and full replacement of natural coarse aggregate by recycled coarse aggregate. A total of one hundred and sixty five (165) concrete samples were investigated respectively and these consists of 12 standard cubes of 100 x 100 x 100 mm, 12 standard cylinders of 100 mm diameter and 200 mm high, 9 standard prisms of 100 x 100 x 500 mm for each concrete mix in Series 4. The results, discussion and summary of findings obtained from fresh concrete sample testing (slump) and hardened concrete sample testing (compressive strength test, flexural strength test, tensile splitting strength test, static modulus of elasticity, and water permeability (Autoclam) are described respectively under this chapter.

The conclusions from chapter four were;

1) Significant reductions in physical and mechanical characteristics of fibre reinforced recycled aggregate concrete as percentage content of recycled coarse aggregate

increased and at higher dosage rate of synthetic macro fibre;

2) The inclusion of 54mm synthetic macro fibre in all the mixes in Series 1-3 produced an insignificant impact on compressive strength of recycled aggregate concrete whereas it improves the flexural strength, tensile splitting strength and static modulus of elasticity respectively.

5.2 Slump test

The results of workability test for each of the concrete mix incorporating 0%, 25%, 50%, 75%, and 100% recycle coarse aggregate respectively is given in Table 33.

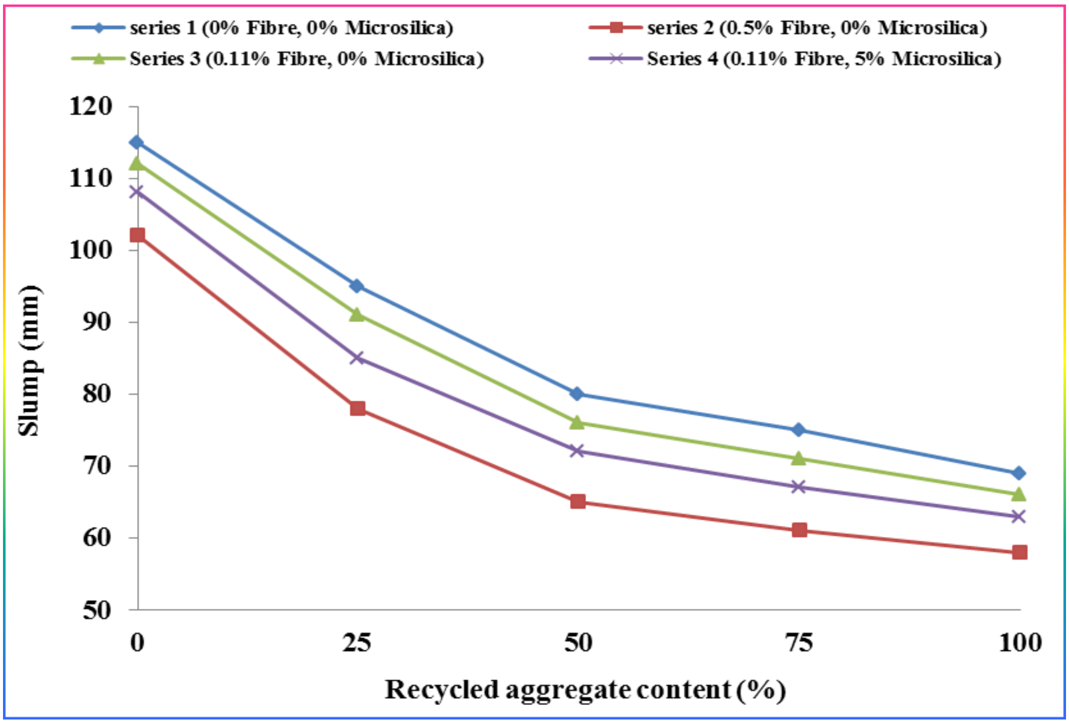
Table 33: Result of slump test for Series 1- 4 concrete mix

RCA (%)	Series 1 (0% F, 0% M) (mm)	Series 2 (0% F, 0% M) (mm)	Series 3 (0.11% F, 0% M) (mm)	Series 4 (0.11% F, 5% M) (mm)
0	115	102	112	108
25	95	78	91	85
50	80	65	76	72
75	75	61	71	67
100	69	58	66	63

RCA --- Recycled Coarse Aggregate, F --- Fibre, M --- Microsilica

Results of Series 1-3 concrete mix have been reported and discussed in chapter 4 and the comparison of these results with the concrete mix incorporating 5% microsilica addition will be discussed. From the laboratory observation, concrete mixes in Series 4 prior to addition of superplasticiser had very low workability in comparison with other concrete mix in Series 1-3. This reduction emanated from the increase in water demand due to the very large surface area of microsilica particles required to be wetted from the free-water. This rendered the concrete less workable while the increasing content of recycled coarse aggregate also affected the workability. However, the incorporation of superplasticiser mitigated this impediment in order to keep the initial specified workability target between 60 and 180 mm and maintaining a constant low water-cement ratio. Results of various slump tests for concrete mixes in Series 4 lie within the target initial workability. The incorporation of microsilica in the mix significantly affects the characteristics of fresh concrete due to the strong cohesiveness of the concrete mix which result in very little bleeding or absence of bleeding in the concrete mix.

The slump results indicate that the maximum value of 108 mm was measured at 0% recycled coarse aggregate content while the minimum value of 63 mm, which represents about 42% relative reduction from the maximum value in Series 4 was obtained at 100% recycled coarse aggregate content. Similar results were recorded in Series 1, 2, and 3 respectively. Mazloom et al. (2004), reported similar reductions in workability of concrete incorporated with microsilica. Results show that Series 4 concrete mixes incorporating microsilica required higher dosages of superplasticiser in order to reach the initial slump target due to the very fine particle size of micro silica. A careful comparison of these results across the concrete mixes indicated that workability decreases as the percentage content of recycled coarse aggregate increases due to higher rate of water absorption associated with recycled aggregate. This view was shared by other researchers (Etxeberria et al. (2007a); Zaidi (2009); Patil et al. (2013)). Figure 59 illustrates the relationship between concrete workability and recycled coarse aggregate content in the mix showing the decreasing trend in workability from Series 1-4 respectively.



RCA --- Recycled Coarse Aggregate, F --- Fibre, M --- Microsilica

Figure 59. Decreasing pattern in slump with increasing recycled aggregate content

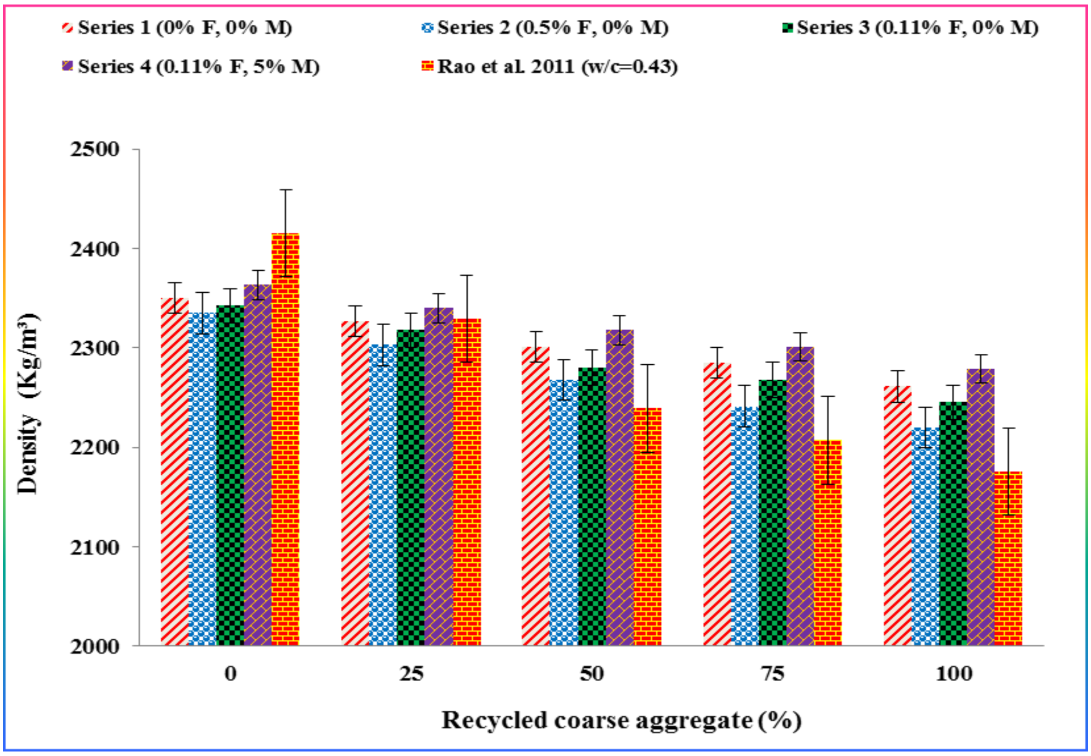
5.3 Density of Concrete

The results of fresh concrete density and hardened concrete cube density recorded for each of the concrete mix incorporating 0%, 25%, 50%, 75%, and 100% recycle coarse aggregate respectively in Series 1 - 4 are given in Tables 34 and 35 with graphical representation in figures 60 and 61 respectively. Series 4 concrete mixes incorporating 5% microsilica and 0.11% synthetic macro fibre produced concrete densities which are more than densities recorded in Series 1, 2, and 3 respectively. This observation is due to the action of microsilica which densified the concrete. This also reduces the effect of the fibre compared with Series 3 which has high fibre volume with entrained air, thereby preventing full compaction.

Table 34: Result of fresh density recorded for Series 1-4 concrete mix

RCA (%)	Series 1 (0% F, 0% M) (kg/m³)	Series 2 (0.5% F, 0% M) (kg/m³)	Series 3 (0.11% F, 0% M) (kg/m³)	Series 4 (0.11% F, 5% M) (kg/m³)
0	2350	2335	2342	2363
25	2327	2303	2318	2340
50	2301	2268	2280	2318
75	2285	2241	2268	2301
100	2261	2220	2245	2279

RCA --- Recycled Coarse Aggregate, F --- Fibre, M --- Microsilica



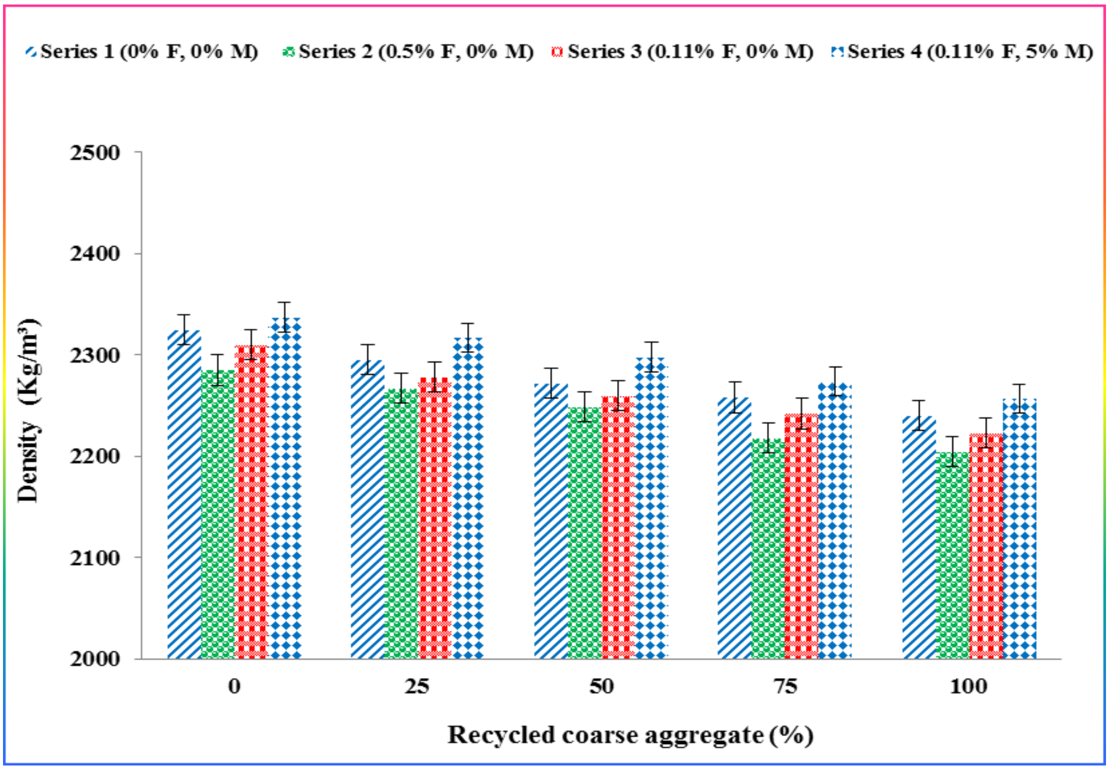
RCA --- Recycled Coarse Aggregate, F --- Fibre, M --- Microsilica

Figure 60: Variation in fresh concrete density with recycled coarse aggregate contents

Table 35: Result of hardened concrete cube density for Series 1-4 concrete mix

RCA (%)	Series 1 (0% F, 0% M) (kg/m³)	Series 2 (0.5% F, 0% M) (kg/m³)	Series 3 (0.11% F, 0% M) (kg/m³)	Series 4 (0.11% F, 5% M) (kg/m³)
0	2325	2285	2310	2337
25	2295	2267	2278	2317
50	2272	2249	2260	2298
75	2258	2218	2242	2274
100	2240	2205	2223	2257

RCA --- Recycled Coarse Aggregate, F --- Fibre, M --- Microsilica

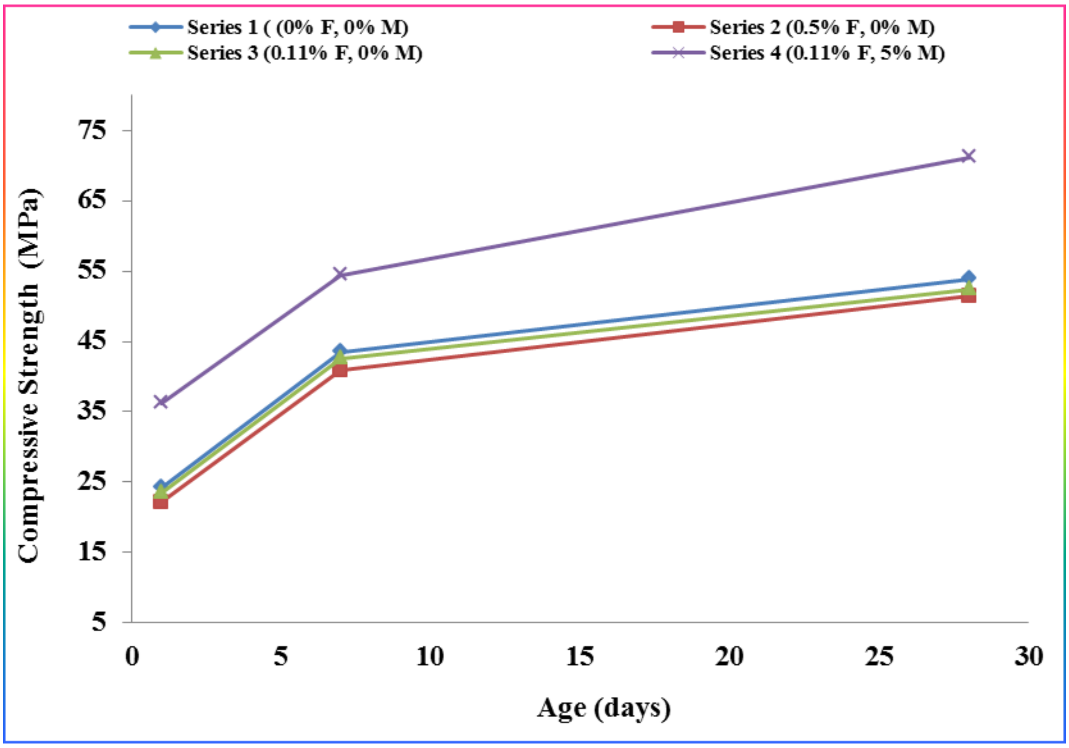


RCA --- Recycled Coarse Aggregate, F --- Fibre, M --- Microsilica

Figure 61. Variation in 28-days hardened concrete cube density with recycled coarse aggregate contents

5.4 Compressive cube strength test

Figures 62-66 illustrates the compressive cube strength of each concrete mix in Series 1-4 at 1, 7, and 28-day curing age respectively with various recycled coarse aggregate content between 0-100% at 25% interval. Results of Series 1-3 concrete mixes was discussed in chapter 4 while further discussion would focus on comparison of results obtained from Series 4 and Series 1-3 concrete mixes respectively.

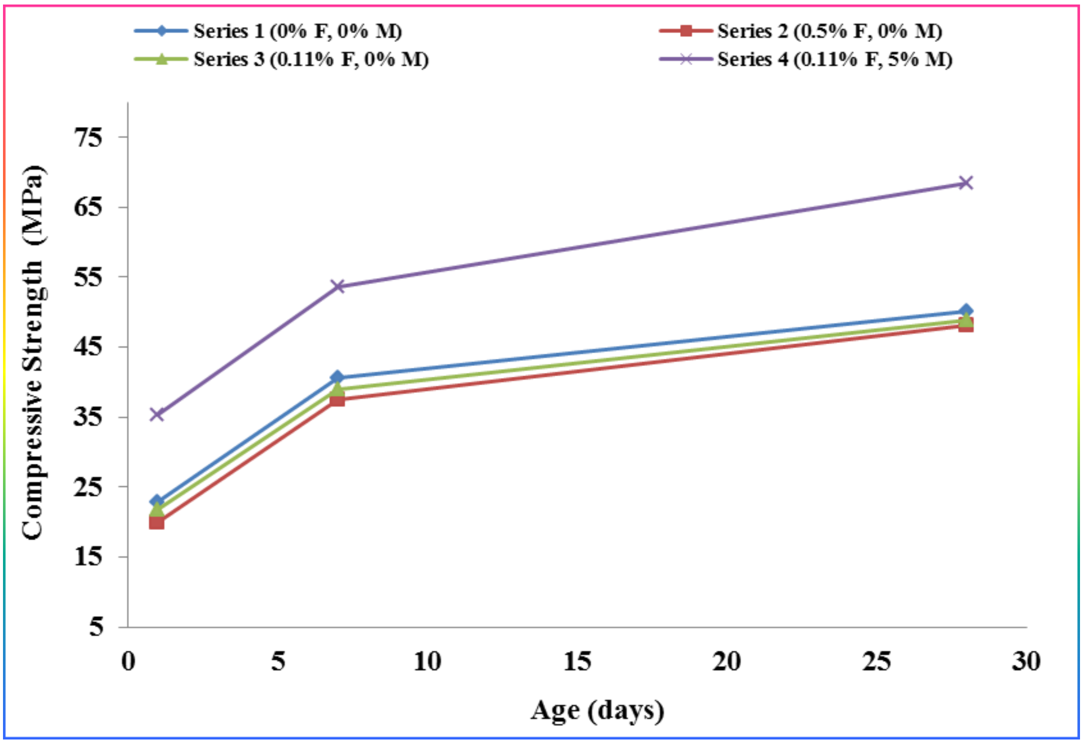


RCA --- Recycled Coarse Aggregate, F --- Fibre, M --- Microsilica

Figure 62. Compressive cube strength at 0% recycled coarse aggregate content

Results from Series 1-4 illustrated in figure 62 above produced the highest compressive cube strengths of about 54MPa, 50MPa, 52MPa, and 71MPa in series 1, 2, 3 and 4 at 28-day curing age respectively. The plot shows that only the concrete mix in Series 4 had 28-day compressive cube strength exceeding the specified 28-day characteristic cube strength of 50MPa and target compressive cube strength of 63MPa. The relative compressive cube strength gained by concrete mix in Series 4 with reference to the corresponding mixes in Series 1, 2, and 3 were 32.1%, 38.1%, and 35.8% respectively.

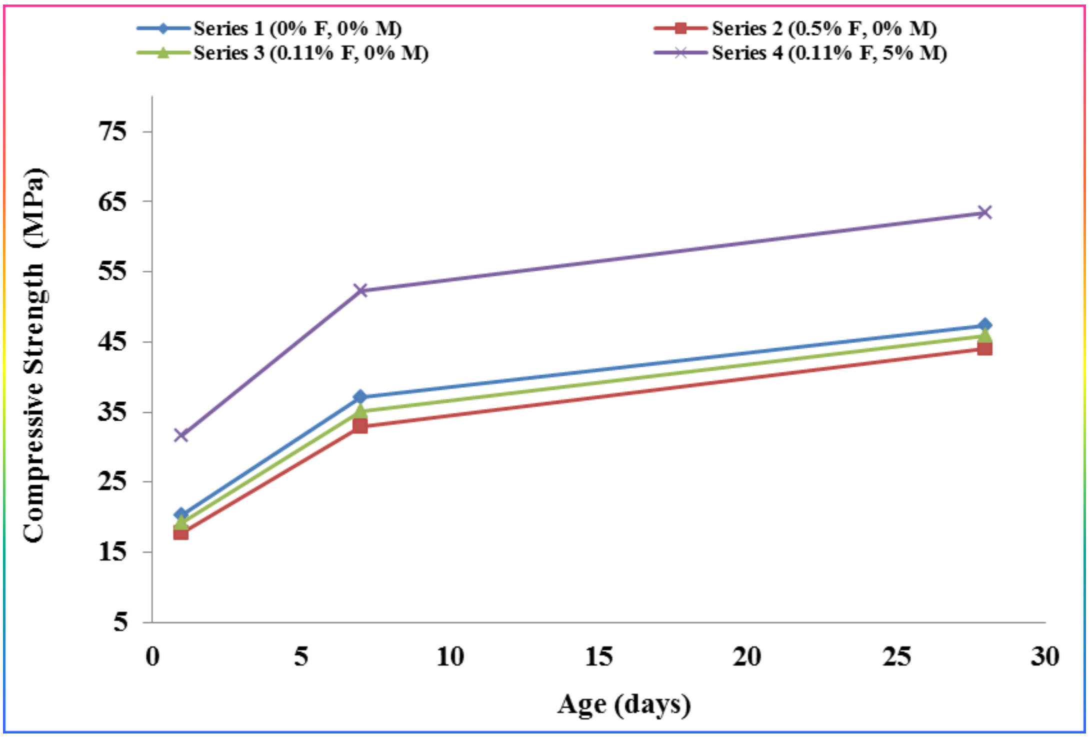
This implies that Series 4 concrete mix incorporated with microsilica produced the best results. The immense contribution of microsilica in strength development of concrete mix in Series 4 could be linked with microsilica's action as a micro filler due to the extreme fineness of the particles (about 100 times smaller than cement particles which improved the parking arrangement of the particles and the interfacial zone between the aggregate and cement paste. The pozzolanic action of microsilica with calcium hydroxide also enhanced the early age strength development of concrete mix in Series 4.



RCA --- Recycled Coarse Aggregate, F --- Fibre, M --- Microsilica

Figure 63. Compressive cube strength at 25% recycled coarse aggregate content

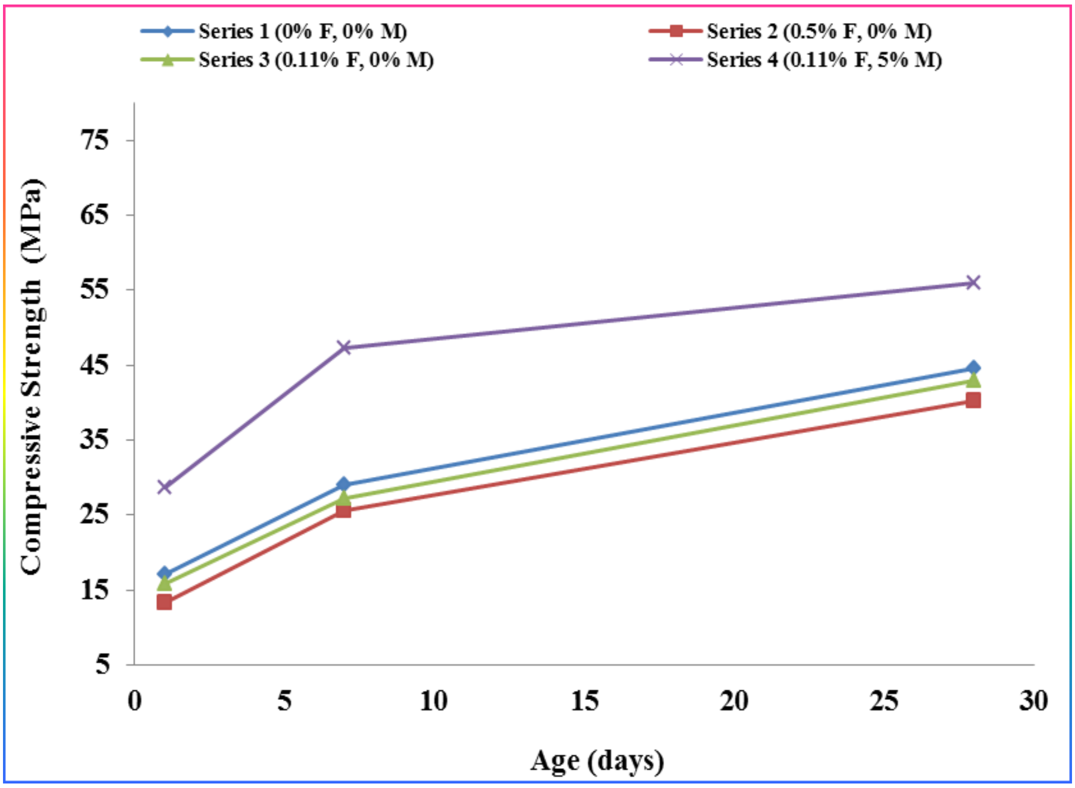
Figure 63 illustrate the results of 1, 7, and 28-day compressive cube strength of concrete mixes in Series 1-4 at 25% recycled coarse aggregate content. The plot shows that Series 4 concrete mix had 28-day compressive cube strength increase of about 36.6%, 42.1%, and 39.9% respectively which correspond to 28-day compressive cube strength of concrete mixes in Series 1, 2 and 3 respectively. The 28-day compressive cube strength of Series 4 concrete mix exceed the specified characteristics compressive cube strength of 50MPa at 28-day and target mean strength of 63MPa respectively whereas Series 1-3 fell below these. This implies that the influence of 25% recycled coarse aggregate content has little or no significant on Series 4 mix.



RCA --- Recycled Coarse Aggregate, F --- Fibre, M --- Microsilica

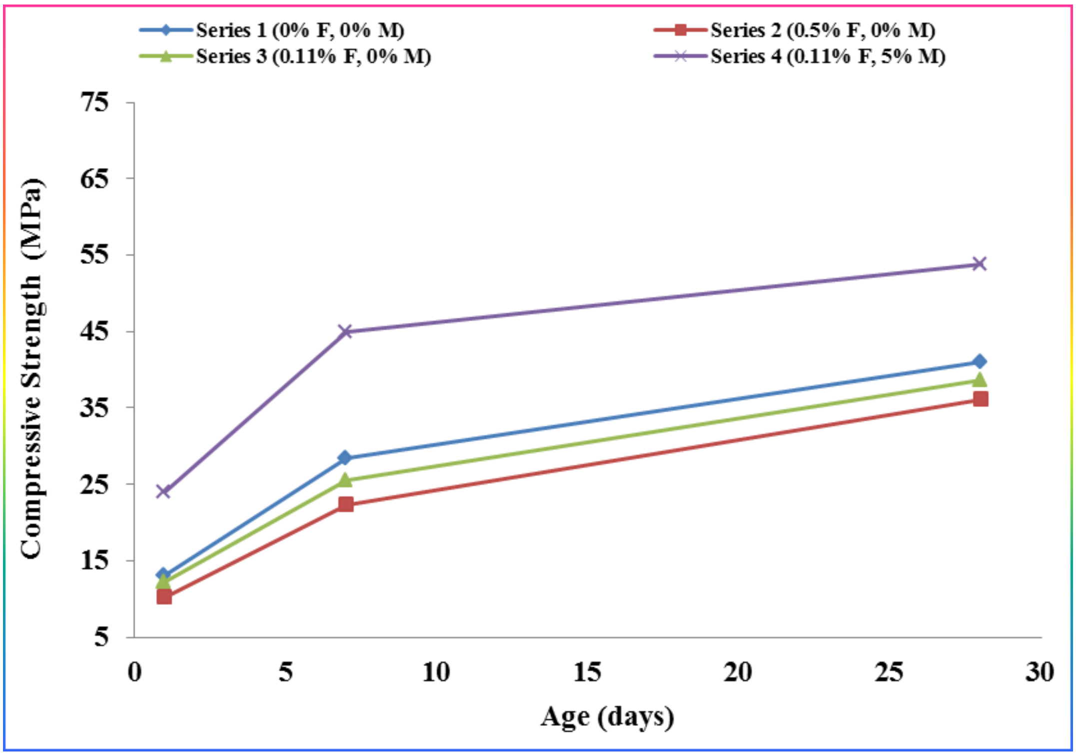
Figure 64. Compressive cube strength at 50% recycled coarse aggregate content

Figures 64 and 65 illustrate the results of 1, 7, and 28-day compressive cube strength for concrete mixes in Series 1-4 at 50% and 75% recycled coarse aggregate content respectively. The increase in 28-day compressive cube strength of concrete mixes in Series 4 were 34.2%, 43.8%, and 38.4% respectively relative to the 28-day compressive cube strength of concrete mixes in Series 1, 2 and 3 respectively. Similar strength increase in Series 4 concrete mixes of about 25.5%, 39.1%, and 30% with reference to Series 1, 2, and 3 respectively were recorded at 75% recycled coarse aggregate content. The 28-day compressive cube strength of Series 4 concrete mix at 50% recycled coarse aggregate content exceeded the specified 28-day characteristics compressive cube strength of 50MPa and target mean strength of 63.1MPa while at 75% recycled aggregate content, the compressive strength only exceed the 28-day characteristics strength but fell below the target mean compressive strength. This implies that the impact of 50% recycled coarse aggregate was insignificant in Series 4 concrete mix.



RCA --- Recycled Coarse Aggregate, F --- Fibre, M --- Microsilica

Figure 65. Compressive cube strength at 75% recycled coarse aggregate content



RCA --- Recycled Coarse Aggregate, F --- Fibre, M --- Microsilica

Figure 66. Compressive cube strength at 100% recycled coarse aggregate content

Results of 1, 7, and 28-day compressive cube strength with substitution of natural coarse aggregate by 100% recycled coarse aggregate illustrated in figure 66 shows that the strength increase in Series 4 concrete mixes with reference to concrete mixes in Series 1, 2, and 3 were 31.5%, 49.3%, and 39.3% respectively. The 28-day compressive cube strength of Series 4 concrete mix at 100% recycled coarse aggregate content also exceed the specified 28-day characteristics compressive cube strength of 50MPa but fell below the target mean compressive strength of 63.1MPa. This implies that the impact of 100% recycled coarse aggregate is slightly significant in Series 4 concrete mix, however the result is much better than Series 1-3 concrete mixes. The general implication of these results is that for a given recycled coarse aggregate content, the addition of 5% microsilica significantly improved the compressive cube strength at 1, 7, and 28-day curing age respectively. Verma et al. (2012), reported an increase of more than 25% in compressive strength when microsilica was incorporated into concrete mix. The strength increase emanated from the reaction between the fine particles of microsilica and the lime content in cement, which led to reduction in voids in the concrete. Alhozaimy et al. (1996), mentioned that microsilica increased the compressive strength by 17% of the control concrete and 23% of concrete incorporated with fibre.

Although microsilica addition produced higher compressive strength, it is worthwhile to mention that there was a general reduction in compressive strength as the recycled coarse aggregate content in Series 4 concrete mix increases. Corinaldesi and Moriconi (2009), corroborated this findings and both authors attributed the results to higher porosity that weakened the recycled coarse aggregate. Poon et al. (2004), identified about 24% reduction in compressive cube strength of concrete incorporating 100% recycled aggregate as the percentage content increases. Similar findings were reported by Adnan et al. (2011) and Kumutha and Vijai (2008) revealed that the higher the recycled coarse aggregate content in a concrete mix, the lower the compressive strength produced when compared with concrete containing less quantity of recycled aggregate. While the percentage recommended use of recycled aggregate in concrete mix stands at 30% (BSI, 2000), the result of compressive cube strength illustrated in figure 64 at 50% recycled coarse aggregate content, suggests that there is a potential to increase the optimum fraction of recycled coarse aggregate in concrete production from 30% to 50% without any significant cause for concern in terms of strength. Figures 67-71 displayed various patterns of failed concrete cubes identified during compressive cube strength test.

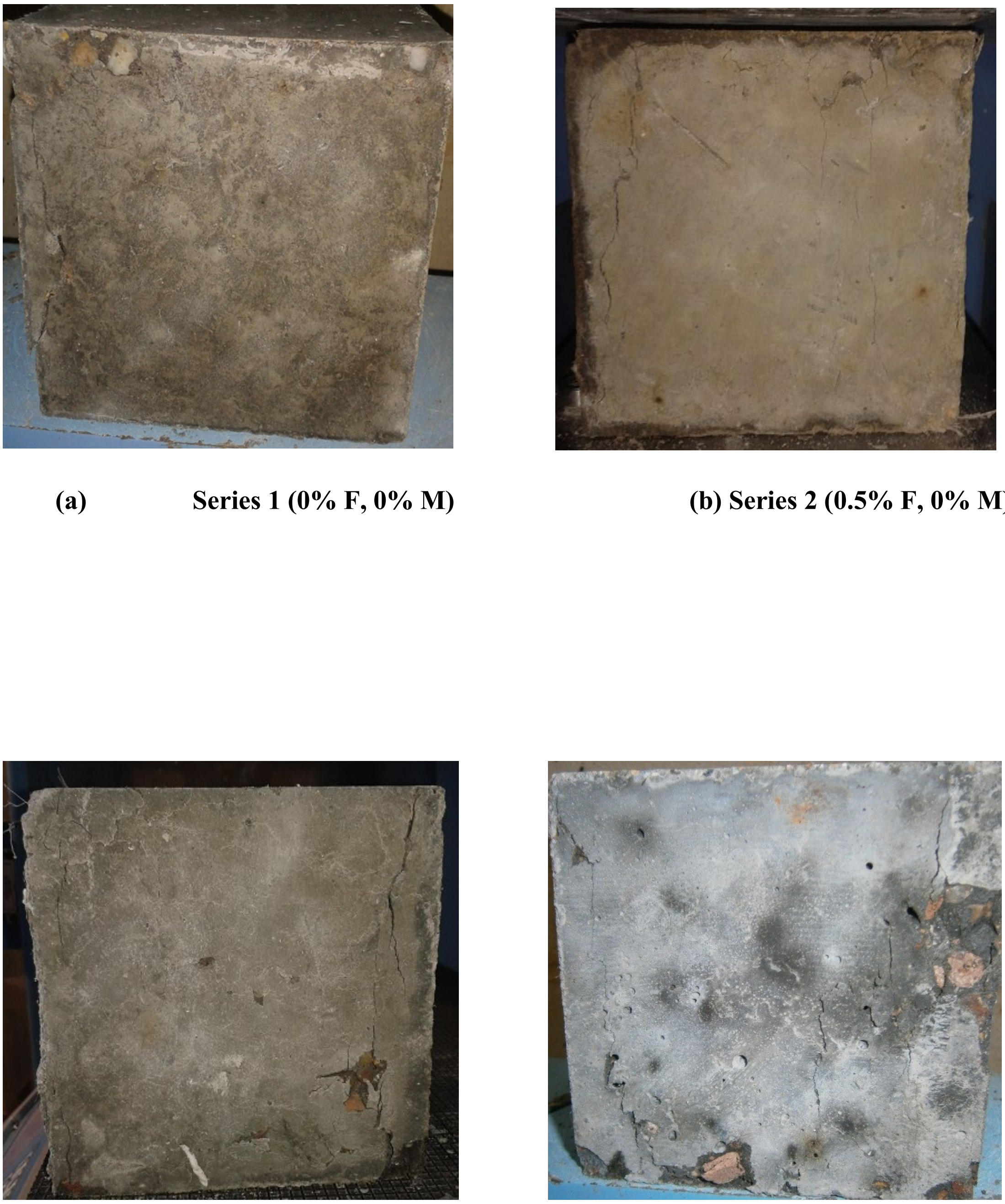
(a) Series 1 (0% F, 0% M)

(b) Series 2 (0.5% F, 0% M)

(c) Series 3 (0.11% F, 0% M)

(b) Series 4 (0.11% F, 5% M)

Figure 67. Failure patterns of cube specimens at 28-days compression test (0% RCA)



(a) Series 1 (0% F, 0% M) (b) Series 2 (0.5% F, 0% M)

(c) Series 3 (0.11% F, 0% M) (d) Series 4 (0.11% F, 5% M)

Figure 68. Failure patterns of cube specimens at 28-days compression test (25% RCA)

(a) Series 1 (0% F, 0% M)

(b) Series 2 (0.5% F, 0% M)

(c) Series 3 (0.11% F, 0% M)

(d) Series 4 (0.11% F, 5% M)

Figure 69. Failure patterns of cube specimens at 28-days compression test (50% RCA)

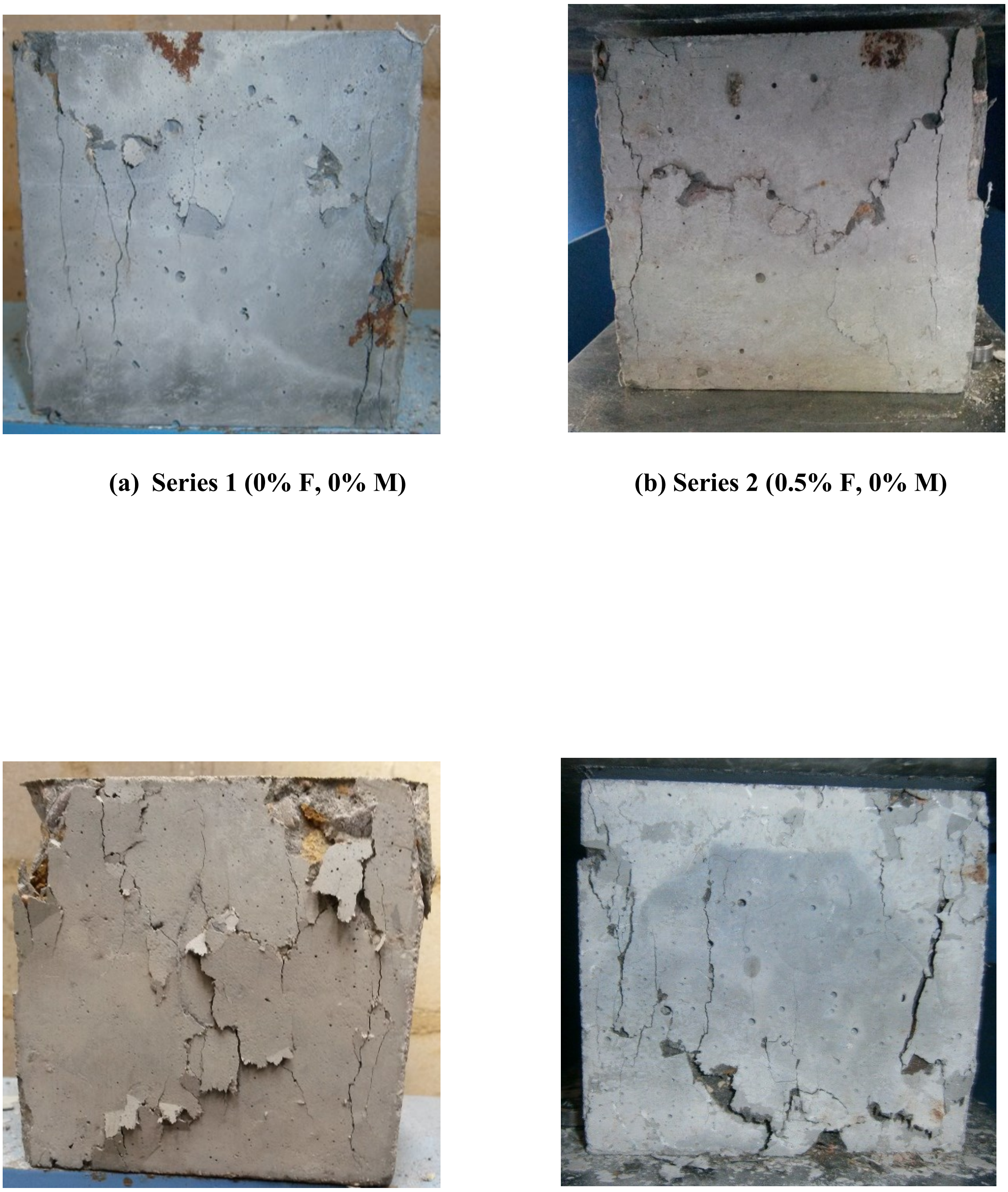
(a) Series 1 (0% F, 0% M)

(b) Series 2 (0.5% F, 0% M)

(c) Series 3 (0.11% F, 0% M)

(d) Series 4 (0.11% F, 5% M)

Figure 70. Failure patterns of cube specimens at 28-days compression test (75% RCA)



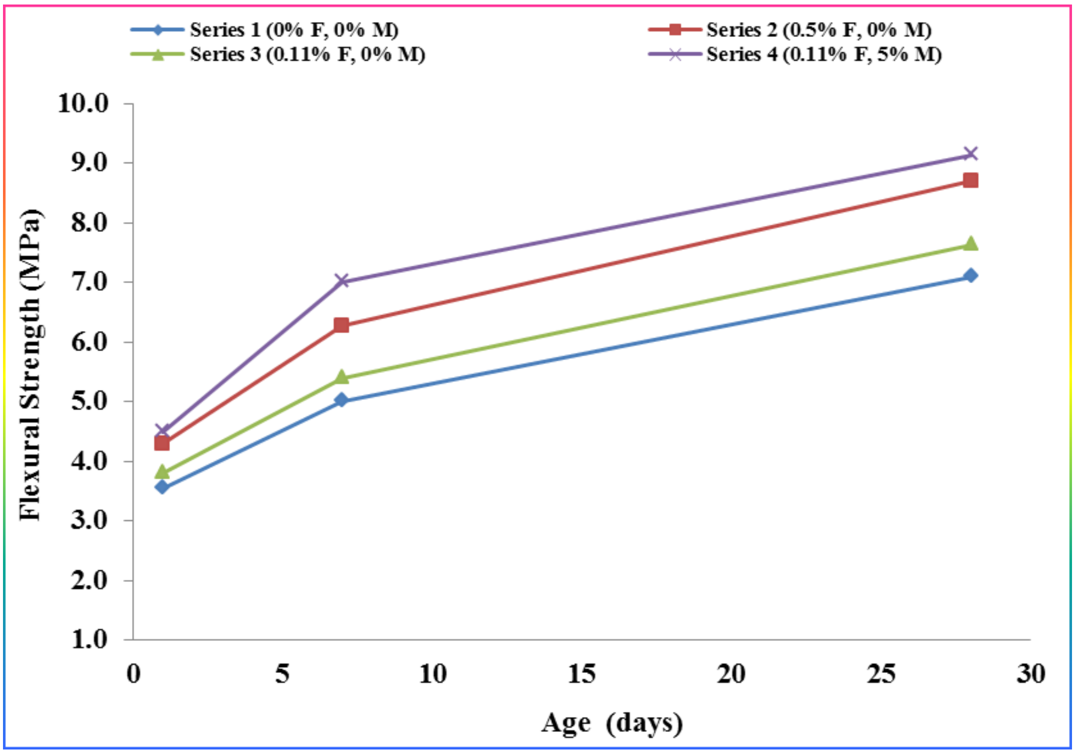
(a) Series 1 (0% F, 0% M) (b) Series 2 (0.5% F, 0% M)

(c) Series 3 (0.11% F, 0% M) (d) Series 4 (0.11% F, 5% M)

Figure 71. Failure patterns of cube specimens at 28-days compression test (100% RCA)

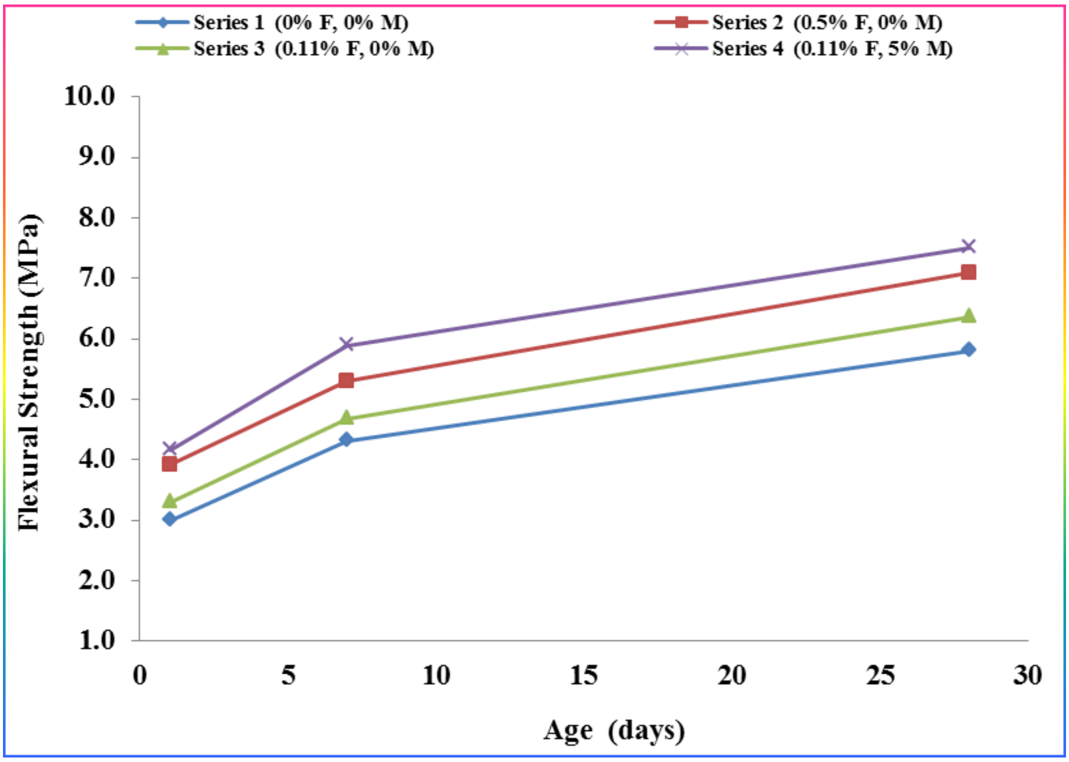
5.5 Flexural strength test

Figures 72-76 illustrates the flexural strength results of concrete mixes in Series 1-4 at 1, 7, and 28-day curing age respectively. For a given percentage of recycled coarse aggregate, the concrete mixes in Series 1 (control) without synthetic macro fibre and microsilica addition, had the least flexural strengths as explained under chapter 4. However, a comparison between Series 1-3 and Series 4 concrete mixes illustrated in figures 72 and 73 respectively, shows that at 0% recycled aggregate content, Series 4 concrete mixes had flexural strengths that were 28.6%, 4.94%, and 19.7% respectively higher than the corresponding mix in Series 1, 2, and 3 while at 25% recycled coarse aggregate content, the relative strength gained by Series 4 concrete mixes were 29.3%, 5.6%, and 18.1% respectively with reference to Series 1, 2, and 3.



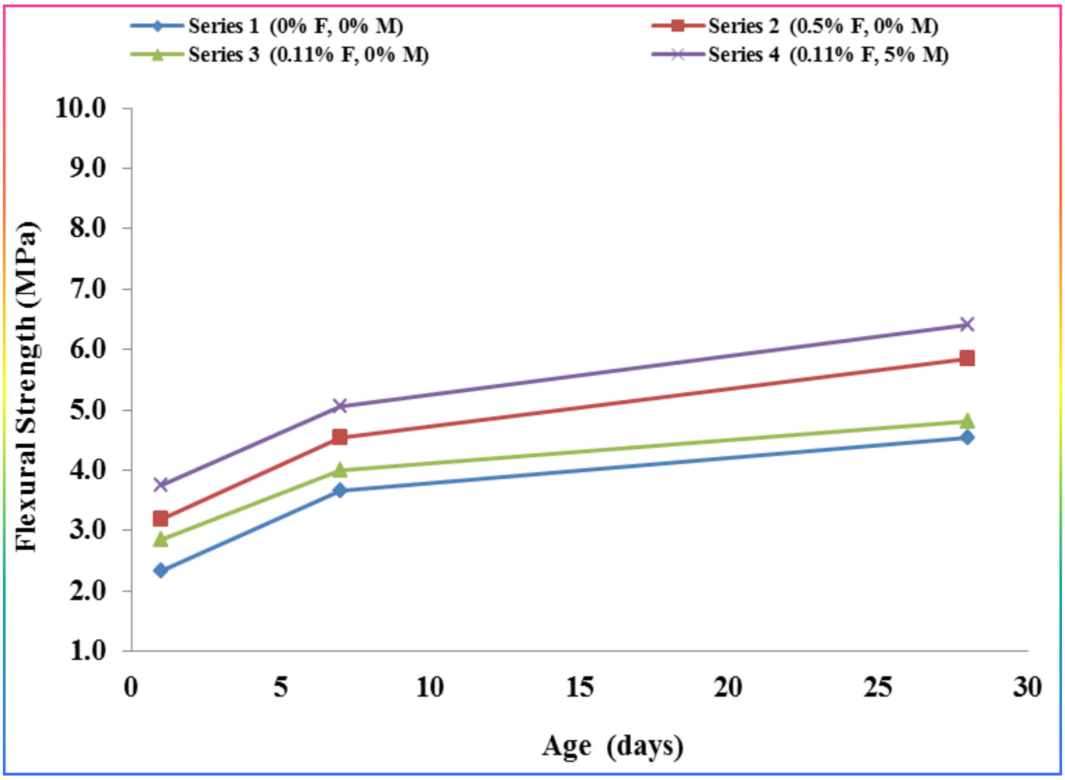
RCA --- Recycled Coarse Aggregate, F --- Fibre, M --- Microsilica

Figure 72. Flexural strength at 0% recycled coarse aggregate content



RCA --- Recycled Coarse Aggregate, F --- Fibre, M --- Microsilica

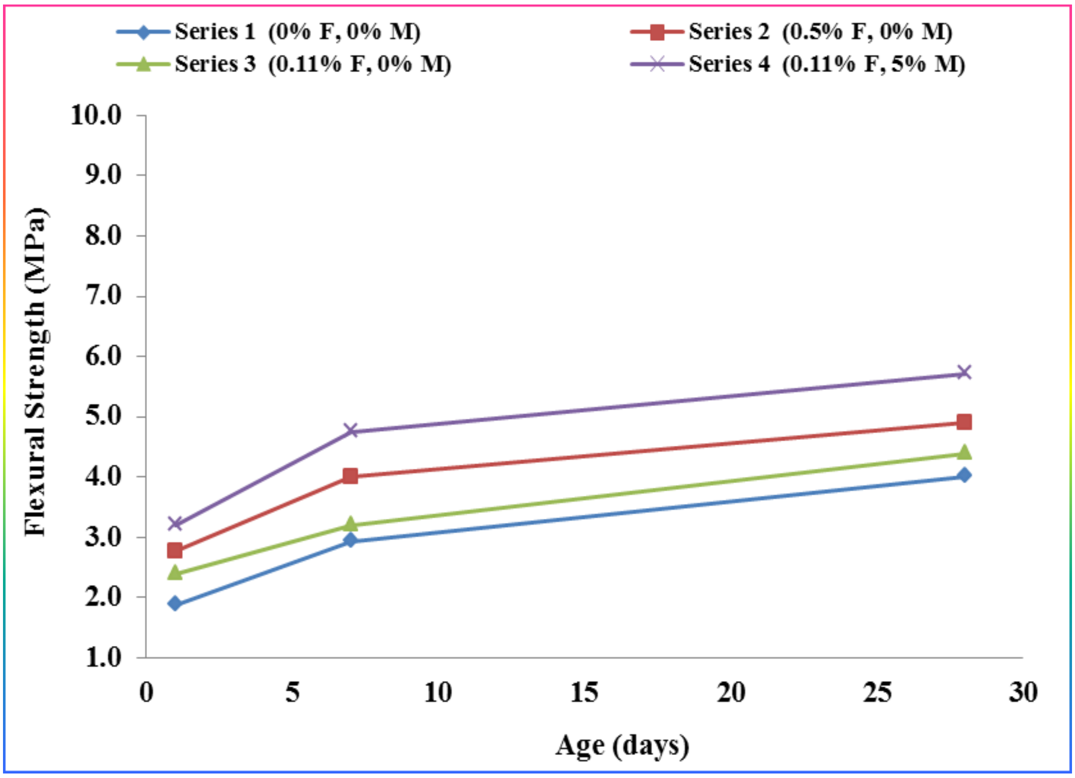
Figure 73. Flexural strength at 25% recycled coarse aggregate content



RCA --- Recycled Coarse Aggregate, F --- Fibre, M --- Microsilica

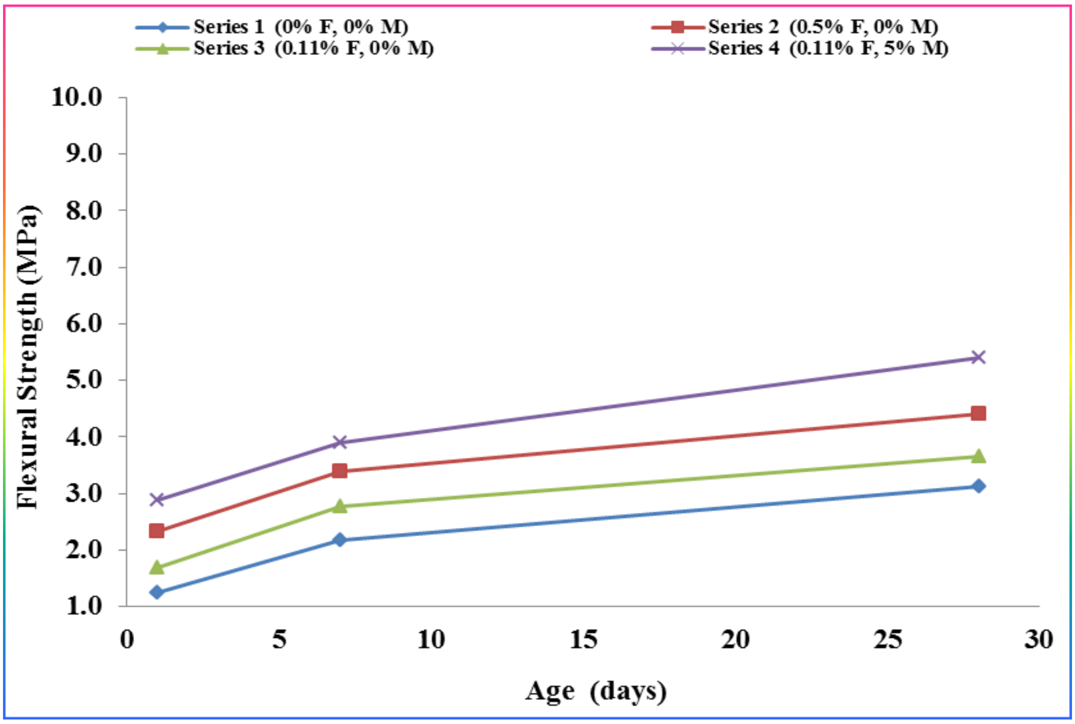
Figure 74. Flexural strength at 50% recycled coarse aggregate content

The flexural strength result in Series 4 concrete mix shown in figure 75 were 40.6%, 9.6%, and 33.1% respectively higher than the corresponding concrete mixes in Series 1, 2, and 3 at 28-day curing age, while the strength gained at 75% recycled coarse aggregate content were 42.5%, 16.1%, and 30.1% respectively. The disparity between the concrete mix in Series 1 and 4 increases due to the significant effect of increasing percentage substitution of natural coarse aggregate with recycled coarse aggregate. However, the disparity between Series 2 and 4 was insignificant due to the incorporation of higher fibre dosage. The incorporation of low fibre dosage in Series 3 also reduced the impact of increase in recycled coarse aggregate content in the mix although there is a wide difference when compared with Series 4 concrete mix. However the result is not too significant as is the case with Series 1 concrete mix.



RCA --- Recycled Coarse Aggregate, F --- Fibre, M --- Microsilica

Figure 75. Flexural strength at 75% recycled coarse aggregate content



RCA --- Recycled Coarse Aggregate, F --- Fibre, M --- Microsilica

Figure 76. Flexural strength at 100% recycled coarse aggregate content

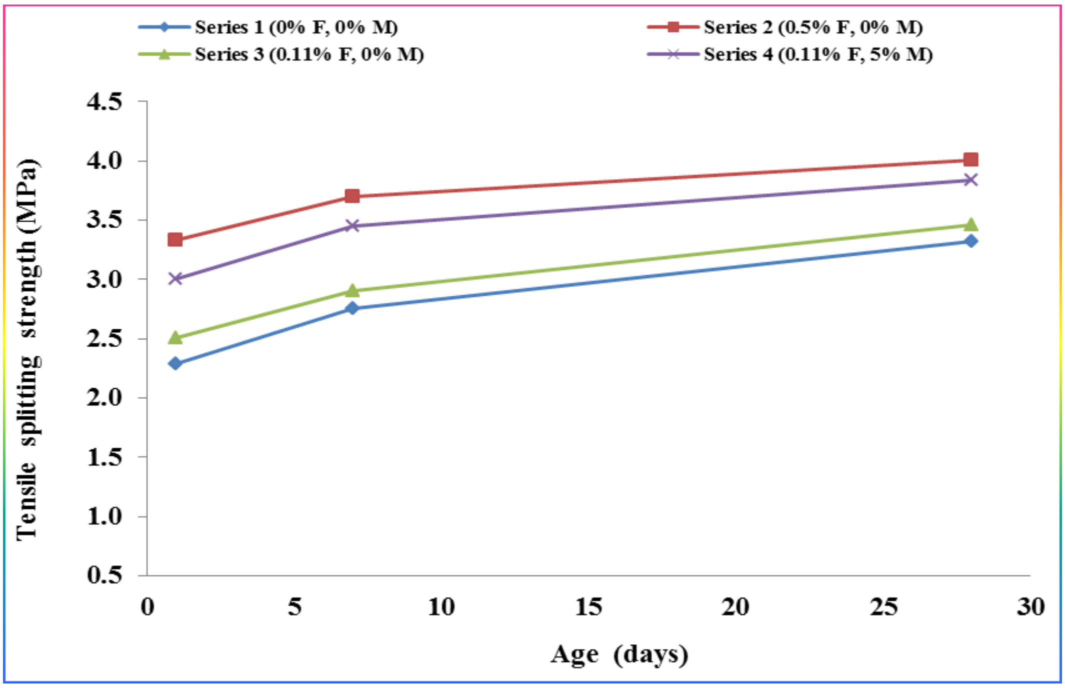
The flexural strength results of concrete mix at 1, 7, and 28-day curing age in Series 1-4 with 100% recycled aggregate content is shown in figure 83. The relative flexural strength gain in Series 4 at 28-day curing age in comparison to the flexural strength results in Series 1, 2, and 3 respectively were 73.1%, 22.7%, and 47.5% respectively. These observations were due to the ductile behaviour of the synthetic macro fibre and their roles in reducing and bridging cracks before failure occurred. Bagherzadeh et al. (2012b), corroborate these explanations. The incorporation of microsilica in Series 4 concrete mixes significantly improved the flexural strengths compared with other corresponding mixes in Series 1-3. Bhanja and Sengupta (2005), corroborated this improvement in flexural strengths of concrete mix incorporated with microsilica. The general observed trend from Series 1-4 concrete mixes shows that with increasing recycled coarse aggregate in the mix, the flexural strength reduces and this reductions were most significant at 100% content and less at 25% content. This observation was similar to findings by Kumutha and Vijai (2008). Various failure modes of concrete prisms identified during flexural strength test are displayed in figure 77.

(a) Series 1 (0% F, 0% M) (b) Series 4 (0.11% F, 5% M)

Figure 77. Failure patterns of prism specimens at 28-days flexural test (0% RCA)

5.6 Tensile splitting strength test

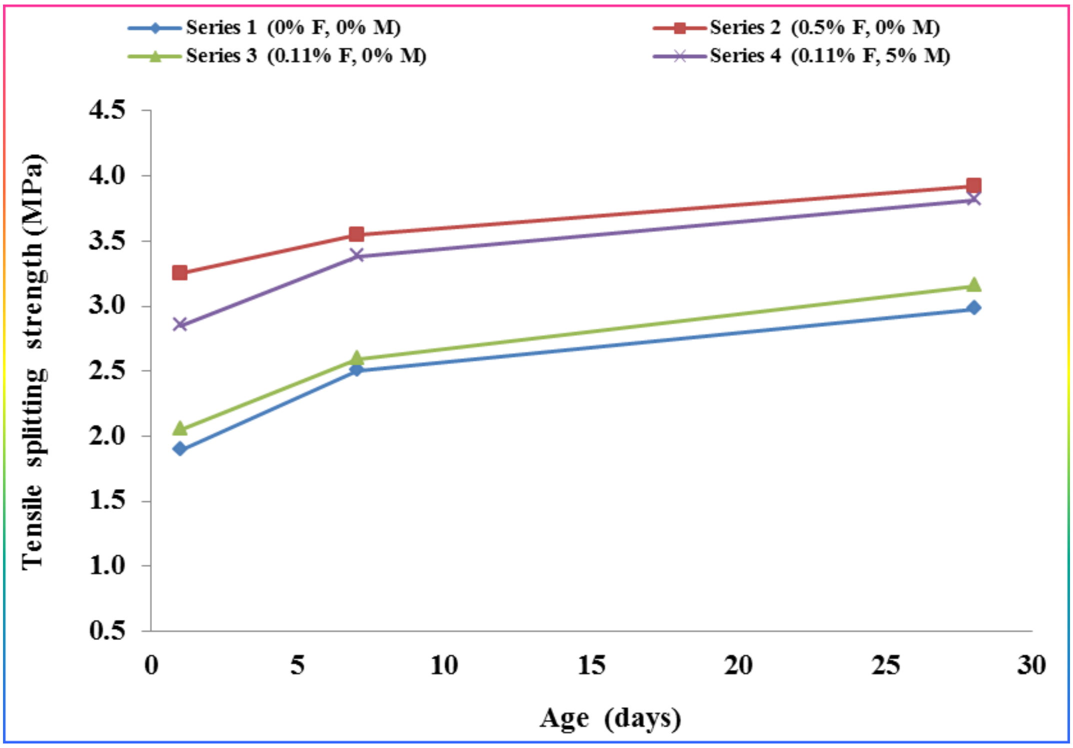
Results of average indirect tensile splitting strength at 1, 7, and 28-day curing age for Series 1, 2, 3, and 4 concrete mixes are illustrated in figures 78 - 82 respectively.



RCA --- Recycled Coarse Aggregate, F --- Fibre, M --- Microsilica

Figure 78. Tensile splitting strength at 0% recycled coarse aggregate content

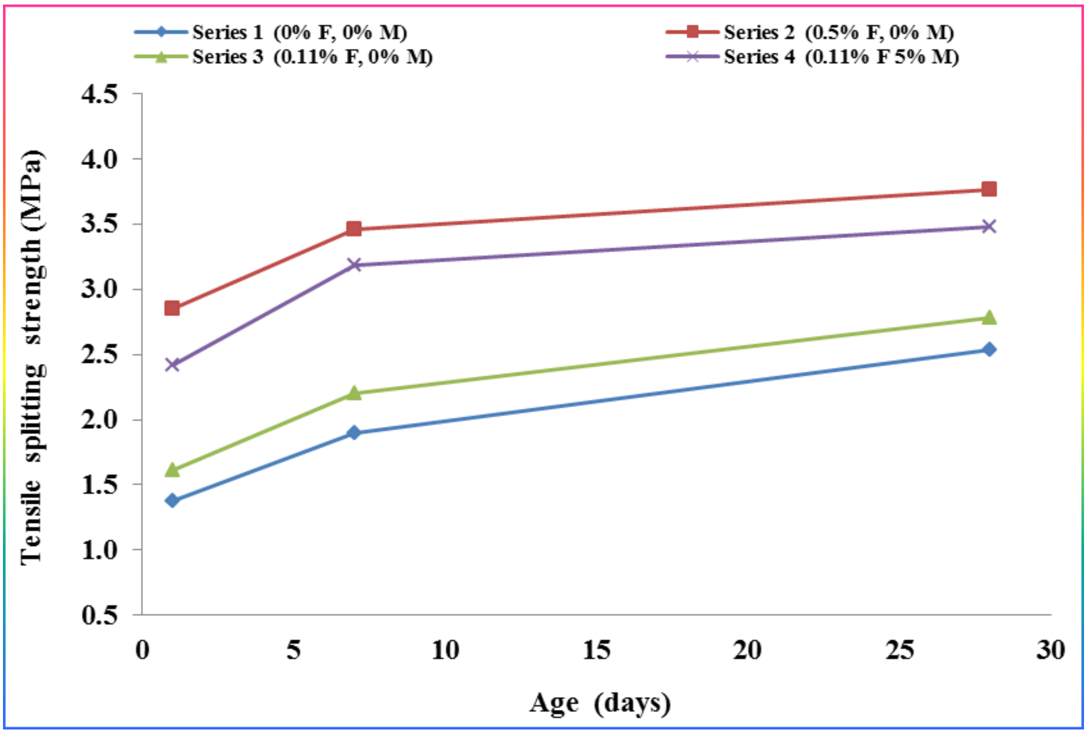
Results of tensile splitting strength from figure 78 indicate that concrete mixes in Series 2 with higher synthetic macro fibre dosage produced better results than concrete mixes in Series 1, 3, and 4 respectively. The 28-day relative strength of Series 2 concrete mix were 20.8%, 15.9% and 4.4% higher that the corresponding mixes in Series 1, 3, and 4 respectively. However, a comparison between Series 1 and 4 concrete mixes illustrated in figures 78 and 79 respectively, shows that at 0% and 25% recycled aggregate content; Series 4 had tensile splitting strengths that were 15.7% and 11% respectively higher than the corresponding mixes in Series 1 at 28-day curing age.



RCA --- Recycled Coarse Aggregate, F --- Fibre, M --- Microsilica

Figure 79. Tensile splitting strength at 25% recycled coarse aggregate content

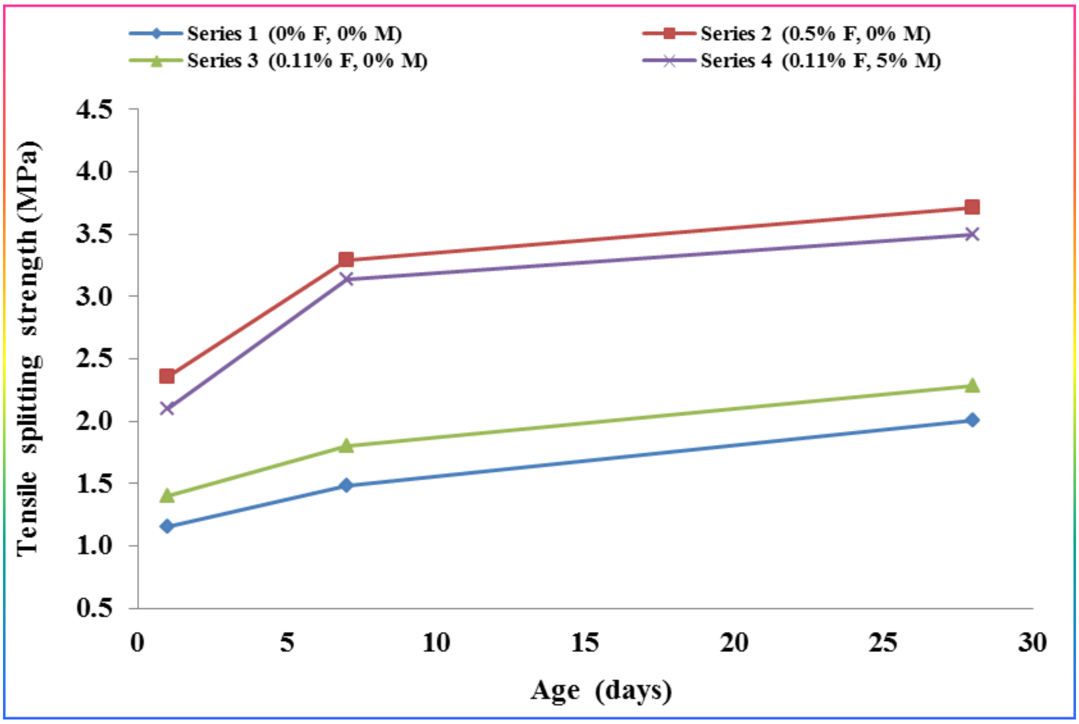
Figure 79 illustrates the tensile spliting strength results of concrete mix in Series 1-4 respectively with 25% recycled coarse aggregate content. The plots shows that Series 2 concrete mix at 28-day curing age had tensile splitting strength of about 31.5%, 24.4%, and 2.9% more than the corresponding mix in Series 1, 3, and 4 respectively. However, Series 3 concrete mix which incorporates lower dosage of synthetic macro fibre, gained about 5.7% tensile splitting strength than Series 1 mix at 28-day curing age . This was due to the incorporation of smaller volume of fibre in the concrete mix.



RCA --- Recycled Coarse Aggregate, F --- Fibre, M --- Microsilica

Figure 80. Tensile splitting strength at 50% recycled coarse aggregate content

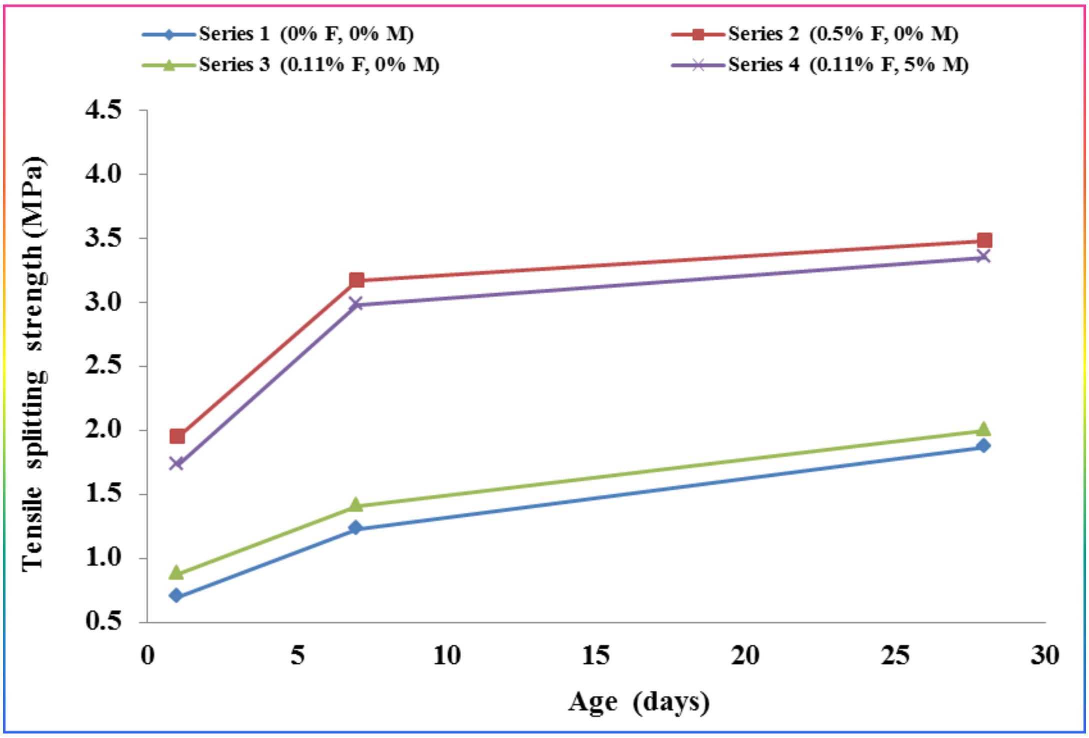
Results of tensile splitting strength of concrete mix incorporating 50% recycled aggregate content is illustrated in figure 80. It was observed that Series 2 concrete mix produced tensile strength result of about 84.6%, 62%, and 6% more than the corresponding mixes in Series 1, 3, and 4 respectively at 28-day curing age. However, Series 4 concrete mixes had about 37% higher tensile splitting strength than corresponding concrete mix in Series 1. These results implies that the effect of increasing percentage recycled coarse aggregate content is significant.



RCA --- Recycled Coarse Aggregate, F --- Fibre, M --- Microsilica

Figure 81. Tensile splitting strength at 75% recycled coarse aggregate content

Figure 81 illustrates the results of tensile spliting strength for concrete mix in Series 1-4 respectively with 75% recycled coarse aggregate content. Series 2 concrete mix at 28-day curing age had tensile splitting strength of about 84.6%, 62%, and 6% more than the corresponding mix in Series 1, 3, and 4 respectively. The results reflects the impact of increasing recycled coarse aggregate in the concrete mix and the influence of synthetic micro fibre addition. However, results of Series 4 concrete mix compared with Series 1 mix at 28-day curing age indicate a strength gain of 74% for Series 4 mix relative to results recorded for Series 1.



RCA --- Recycled Coarse Aggregate, F --- Fibre, M --- Microsilica

Figure 82. Tensile splitting strength at 100% recycled coarse aggregate content

The tensile splitting strength results for concrete mix in Series 1-4 at 1, 7, and 28-day curing age is illustrated in figure 82 above. The relative increase in tensile splitting strength in Series 2 compared with the corresponding concrete mix in Series 1, 3, and 4 respectively at 28-day were 86.1%, 74%, and 3.9% respectively. Series 4 concrete mix had about 79% 28-day tensile splitting strength more than the corresponding mix in Series 1. This indicate a wide disparity at 100% recycled coarse aggregate content between Series 1 and 3 and Series 1 and 4 respectively. However, the disparity indicates the significance of incorporation of microsilica and synthetic macro fibre in Series 4 concrete mixes and the addition of higher dosage of synthetic macro fibre in Series 2.

The addition of microsilica in Series 4 concrete mixes enhanced the tensile splitting strengths in comparison with corresponding mixes in Series 1-3. The disparity between concrete mixes in Series 2 and 4 compared to Series 1 and 3 increases with more recycled aggregate content in the mix. The overall observation shows that results decreased as the recycled aggregate content in all the concrete mixes increases. Evangelista and De Brito (2007), agreed with this observation and attributed the strength reduction pattern to the porous nature of the recycled aggregate. For a given percentage of recycled coarse aggregate, the concrete mixes in Series 1 (control) without synthetic macro fibre and microsilica addition, had the least tensile splitting strengths as explained under chapter 4.

Kou et al. (2011), associated the tensile splitting strength increase to the improved microstructure of the interfacial transition zone and increased bond strength between new cement paste and recycled aggregate catalysed by addition of microsilica (Pauw and Lauritzen). Bhanja and Sengupta (2005), reported an increase in tensile splitting strength of concrete incorporated with microsilica and attributed this to the ability of microsilica particles to fill the voids in concrete. Various fractured patterns of concrete cylinder observed during the tensile splitting test are shown in figure 83.

(b) Series 1 (0% F, 0% M) **(b) Series 4 (0.11% F, 5% M)**

Figure 83. Failure patterns of prism specimens at 28-days flexural test (0% RCA)

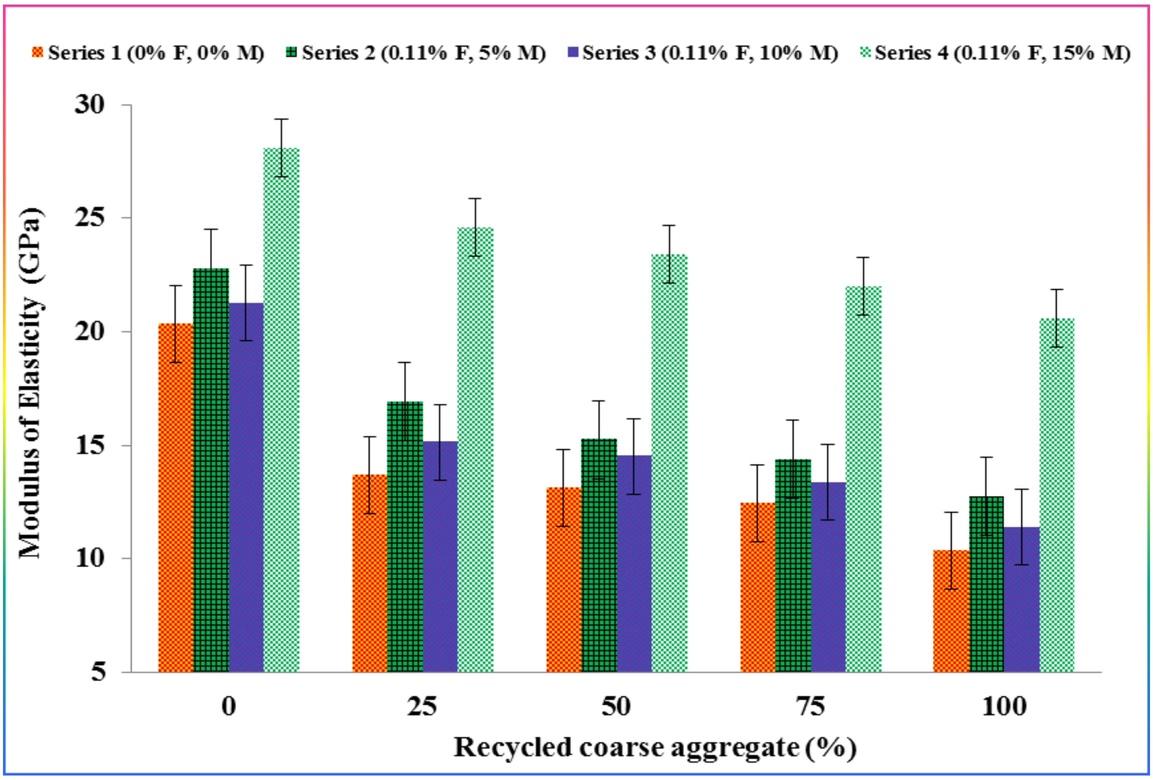
5.7 Static Modulus of Elasticity

Summary of the results of 28-day static modulus of elasticity for concrete mixes in Series 1-4 is given in Table 36 and illustrated in Figure 84 respectively. The results indicates that for a given percentage of recycled coarse aggregate, results from Series 4 concrete mix incorporating synthetic macro fibre and microsilica had the maximum elastic modulus while concrete mixes in Series 1 without synthetic macro fibre and microsilica addition produced the lower results.

Table 36: Summary of result of 28-day static modulus of elasticity

RCA (%)	**Series 1 (0% F, 0% M) (GPa)**	**Series 2 (0.5% F, 0% M) (GPa)**	**Series 3 (0.11% F, 0% M) (GPa)**	**Series 4 (0.11% F, 5% M) (GPa)**
0	20.35	22.79	21.27	28.10
25	13.66	16.91	15.13	24.60
50	13.10	15.25	14.51	23.40
75	12.43	14.38	13.37	22.00
100	10.33	12.74	11.39	20.6

RCA --- Recycled Coarse Aggregate, F --- Fibre, M --- Microsilica



RCA --- Recycled Coarse Aggregate, F --- Fibre, M --- Microsilica

Figure 84. 28-day static modulus of elasticity

There were significant relative gains in modulus of elasticity of Series 4 concrete mixes compared with Series 1. The relative increase in elastic moduli of concrete mixes in Series 4 at 0% and 25% recycled coarse aggregate content were 38.1% and 80% more than the elastic moduli respectively of Series 1 cocnrete mixes. At 50% and 75% recycled aggregate content, the increase in elastic moduli of concrete mix in Series 4 relative to Series 1 were 78.6% and 77% respectively while 99.4% was recorded at 100% recycled coarse aggregate content. These observations mostly revealed the impact of micro silica addition and synthetic macro fibre in concrete mixes in Series 4. However, a general observation shows a decreasing trend of modulus of elasticity as the percentage content of recycled coarse aggregate in the concrete mix increased, and this was due to the lower modulus of elasticity of recycled coarse aggregate when compared to natural coarse aggregate. Similar findings were reported by past studies (Frondistou-

Yannas (1977); Berndt (2009a); Xiao et al. (2005a)) and these reductions in elastic modulus as percentage recycled coarse aggregate in concrete mix increases was associated with the lower modulus of elasticity of recycled coarse aggregate. It is also a fact that concrete is a composite material and its modulus of elasticity is influenced by the elastic moduli of respective constituents which in this experiment were aggregate and the inclusion of synthetic macro fibre.

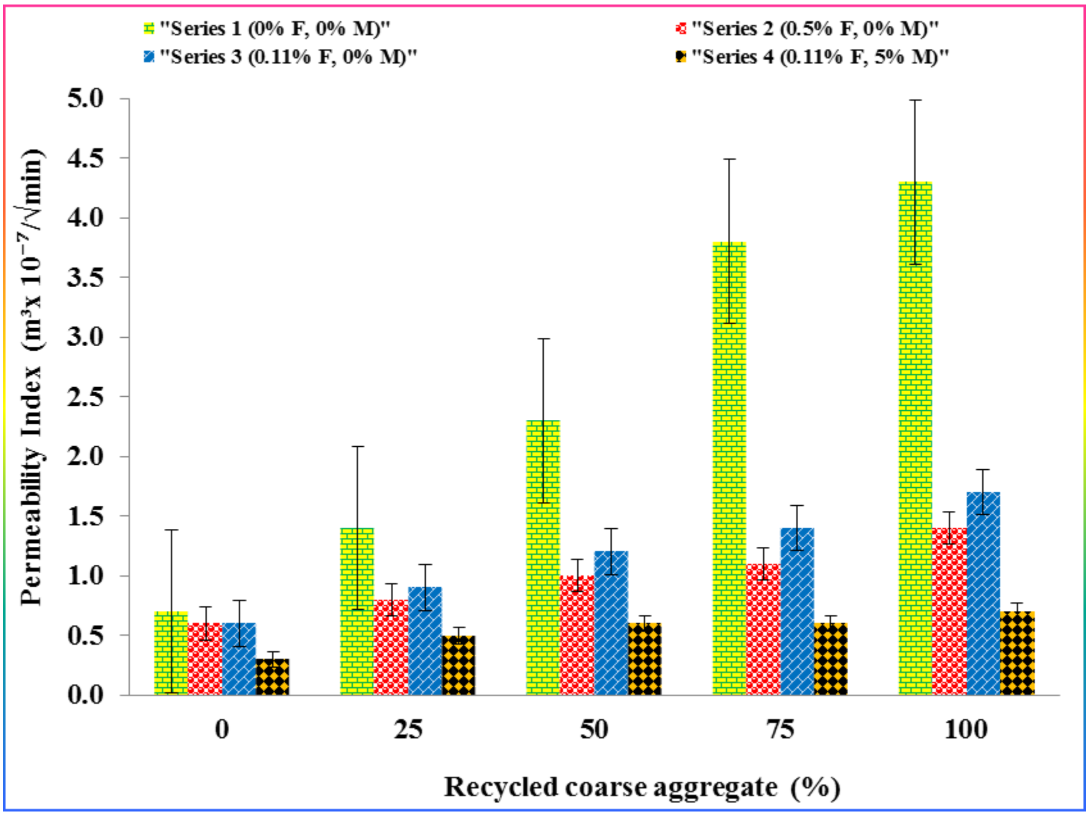
5.8 Water Permeability Test (Autoclam)

Table 37 displayed the summary of sorptivity indices from the results of 28-day water permeability test conducted on Series 1- 4 concrete mix and these results are graphically represented in Figure 85.

Table 37: Summary of sorptivity indices of 28-day permeability test on concrete cubes

RCA (%)	Series 1 (0% F, 0% M) ($m^3 x10^{-7}/\sqrt{min}$)	Series 2 (0.5% F, 0% M) ($m^3 x10^{-7}/\sqrt{min}$)	Series 3 (0.11% F, 0% M) ($m^3 x10^{-7}/\sqrt{min}$)	Series 4 (0.11% F, 5% M) ($m^3 x10^{-7}/\sqrt{min}$)
0	0.7	0.6	0.6	0.3
25	1.4	0.8	0.9	0.5
50	2.3	1.0	1.2	0.6
75	3.8	1.1	1.4	0.6
100	4.3	1.4	1.7	0.7

RCA --- Recycled Coarse Aggregate, F --- Fibre, M --- Microsilica



RCA --- Recycled Coarse Aggregate, F --- Fibre, M --- Microsilica

Figure 85. 28-day water permeability (Autoclam) result

The general trend shows that the higher the percentage content of recycled coarse aggregate in the concrete mix, the higher the sorptivity index and vice-versa. This was due to the porous nature of the recycled coarse aggregate, which tends to increase permeability. For a given percentage recycled coarse aggregate content in the concrete mix, Series 1 mix (control) produced the maximum value of permeability indices at 100% recycled aggregate content, which suggests that it is more porous than other mixes, while Series 4 mix had the least permeability indices at the same recycled aggregate content. Series 3 concrete mix with low synthetic macro fibre dosage had higher sorptivity index than concrete mix in Series 2 with higher dosage of synthetic macro fibre. This implies that higher fibre dosage rendered the concrete less permeable due to their bonding ability thereby reducing water pathway. The synergy between the macro synthetic fibre and micro silica in Series 4 concrete mix greatly influence the permeation property of the concrete produced since micro silica is known to have outstanding micro filler properties.

Table 38: Protective quality of concrete

Protective quality of concrete based on Clam permeation indices after (Concrete-Society, 2008)				
Permeation Property	**Protective Property**			
	Very good	Good	Poor	Very poor
Clam Water Permeability ($m^3x10^{-7}/\sqrt{min}$)	≤ 3.70	> 3.70 ≤ 9.40	> 9.40 ≤ 13.8	> 13.8

According to Table 38, the mixes in Series 2-4 fell under the very good protective quality of concrete while the control mixes in Series 1 fell under very good to good category. The Sorptivity indices of concrete mix in Series 1 at 75% and 100% recycled aggregate content were 3.8 and 4.3×10^{-7} $m^3/\sqrt{min}$ respectively and these fell under good protective quality category. The higher water absorption of the old mortar attached to the recycled coarse aggregate could be linked with the high permeability results recorded in Series 1. Sagoe-Crentsil et al. (2001), suggested that the residual mortal acts like a conduit for water transport.

Similar findings were reported by previous researchers (Limbachiya et al. (2000); Yang et al. (2011); Pandit and Parameswari (2014)). The concrete mixes in Series 4 had the best durability properties due to the dense impermeable microstructure (calcium silica hydrate) formed from the reaction between the calcium hydroxide (lime) present in the cement and microsilica as a result of its very small fine particles size (Neville, 1995). This result in low porosity, capillary and absorption which eventually contributed to reduction in permeability and increased tendency of the the concrete mix in Series 4 to provide resistance against ingress of water. Song et al. (2010), reported that addition of microsilica reduced permeability due to its densifying effect on microstructure thereby reducing porosity which subsequently produce denser concrete.

In general, all the sorptivity indices recorded fell below the $9.4 \times 10^{-7} m^3/\sqrt{min}$ boundary, which represents poor protective quality of concrete as indicated in Table 28. This implies that concrete mixes produced from Series 1-4 are satisfactory as durable concrete.

5.9 Summary of findings

The main conclusions from this experimental work are as follows:

1. The physical and mechanical properties of concrete reduced with increasing recycled coarse aggregate content in the concrete mix;
2. Although the effect of synthetic macro fibre on compressive strength was insignificant, it contributed to the durability of concrete in terms of reducing the flow path of water into the concrete specimen thereby reducing the rate of permeability.

3. Addition of 5% microsilica significantly improved the compressive strength, splitting tensile strength, flexural strength, static modulus of elasticity, and water permeability of concrete mix in Series 4 at any given recycled coarse aggregate content in the concrete mix;
4. The incorporation of 5% microsilica to the concrete mix with 50% recycled coarse aggregate content produced 28-day compressive strength, which exceeds the 28-day characteristic compressive cube strength of 50 MPa, specified in the mix design. This value also exceeded the target mean compressive cube strength of 63MPa.
5. These findings could lead to a step change in the conservation of quarry, reduction in cost of construction materials, and reduce pressure on landfills.
6. The result in (3) above suggests that there is a potential to increase the optimum fraction of recycled coarse aggregate in concrete from 30% to 50% in terms of strength and durability.
7. The static modulus of elasticity of concrete mix in Series 4 similar to the observation in Series 1-3 concrete mix, fell below the theoretical value of 35 GPa given in Table 3.1 of BS-EN 1992-1-1:2004.

6 OPTIMISED USE OF MICROSILICA IN FIBRE REINFORCED AGGREGATE CONCRETE

6.1 Introduction

The results of the evaluation of optimum addition of microsilica required to achieve better performance in fibre reinforced recycled coarse aggregate concrete produced in phase 2 experiment incorporating 54mm forta-ferro synthetic macro fibre and microsilica are discussed under this chapter. The main goal was to determine the percentage content at which the efficiency and effectiveness of microsilica in concrete mix would yield optimum benefit after which further addition would cause decline in engineering properties of the concrete produced.

Sequel to phase 3 experiments, the observations from phase 2 experimental work are;

1. Incorporation of 5% mineral admixture (microsilica) greatly improved the compressive strength, tensile splitting strength, flexural strength, protective quality in terms of water permeability, and elastic modulus of all the concrete mix in Series 4 experimental work irrespective of the percentage recycled coarse aggregates content in the mix;
2. Addition of 5% microsilica to concrete mixes in Series 4 at 50% recycled aggregate content produced 28-day compressive cube strength, which exceeds the 28-day characteristic compressive cube strength of 50MPa and target mean compressive cube strength of 63.1MPa respectively. This suggests that there is a potential to boost the use of recycled coarse aggregate from 30-50%;
3. The static elastic modulus of concrete mix in Series 1-4 fell below the theoretical result of 35GPa given in table 3.1 of BS EN 1992-1-1:2004.

The third phase of the concrete mix design complied with the conventional UK mix design method (BRE, 1997), 'design of normal concrete mix manual'. Eight hundred and eighty five (885) hardened concrete samples produced were subjected to various tests as discussed under chapter 3 from four different concrete mixes shown in tables 26-29 respectively. Each concrete batch consists of 12 standard cubes of 100x100x100 mm, 12 standard cylinders of 100mm diameter by 200mm high, and 15 standard prisms of 100x100x500 mm. Concrete mixes in Series 4–7 incorporates same dosage of synthetic macro fibre of 1kg/m³ by weight of concrete and microsilica addition at 5%, 10%, 15% and 20% respectively. A High Range Superplasticiser (Alphaflow 420) was used as chemical admixture at varying dosages in order to maintain the initial specified workability. The 28-day characteristics compressive cube strength; target mean compressive cube strength, free-water/cement ratio (w/c) and initial specified slump remained the same as in Phase 1 concrete mix. Tables 39-42 displayed details of the concrete mixes used in Series 4-7 respectively.

Table 39: Concrete mix details – Series 4 (0% F, 5% M)

Recycle Aggregate by weight of coarse aggregate. (%)	0	25	50	75	100
Cement (kg/m³)	583	583	583	583	583
Sand (kg/m³)	603	603	603	603	603
Gravel (kg/m³)	904	678	452	226	0
RCA. (kg/m³)	0	226	452	678	904
Water (kg/m³)	230	230	230	230	230
Synthetic Macro Fibre - 0.11% by volume of concrete (kg/m³)	1	1	1	1	1
Microsilica (kg/m³) - 5% by weight of cement	29.2	29.2	29.2	29.2	29.2
Superplasticiser by weight of cement (kg/m³)	2.33	2.33	2.33	3.50	3.50

RCA --- Recycled Coarse Aggregate, F --- Fibre, M --- Microsilica

Table 40: Concrete mix details – Series 5 (0% F, 10% M)

Recycle Aggregate by weight of coarse aggregate. (%)	0	25	50	75	100
Cement (kg/m^3)	583	583	583	583	583
Sand (kg/m^3)	603	603	603	603	603
Gravel (kg/m^3)	904	678	452	226	0
RCA. (kg/m^3)	0	226	452	678	904
Water (kg/m^3)	230	230	230	230	230
Synthetic Macro Fibre - 0.11% by volume of concrete (kg/m^3)	1	1	1	1	1
Microsilica (kg/m^3) - 10% by weight of cement	58.4	58.4	58.4	58.4	58.4
Superplasticiser by weight of cement (kg/m^3)	3.50	3.50	3.50	4.66	4.66

RCA --- Recycled Coarse Aggregate, F --- Fibre, M --- Microsilica

Table 41: Concrete mix details – Series 6 (0% F, 15% M)

Recycle Aggregate by weight of coarse aggregate. (%)	0	25	50	75	100
Cement (kg/m^3)	583	583	583	583	583
Sand (kg/m^3)	603	603	603	603	603
Gravel (kg/m^3)	904	678	452	226	0
RCA. (kg/m^3)	0	226	452	678	904
Water (kg/m^3)	230	230	230	230	230
Synthetic Macro Fibre - 0.11% by volume of concrete (kg/m^3)	1	1	1	1	1
Microsilica (kg/m^3) - 15% by weight of cement	87.6	87.6	87.6	87.6	87.6
Superplasticiser by weight of cement (kg/m^3)	4.66	4.66	4.66	5.83	5.83

RCA --- Recycled Coarse Aggregate, F --- Fibre, M --- Microsilica

Table 42: Concrete mix details – Series 7 (0% F, 20% M)

Recycle Aggregate by weight of coarse aggregate. (%)	0	25	50	75	100
Cement (kg/m³)	583	583	583	583	583
Sand (kg/m³)	603	603	603	603	603
Gravel (kg/m³)	904	678	452	226	0
RCA. (kg/m³)	0	226	452	678	904
Water (kg/m³)	230	230	230	230	230
Synthetic Macro Fibre - 0.11% by volume of concrete (kg/m³)	1	1	1	1	1
Microsilica (kg/m³) - 20% by weight of cement	116.8	116.8	116.8	116.8	116.8
Superplasticiser by weight of cement (kg/m³)	6.41	6.41	6.41	7.00	7.00

RCA --- Recycled Coarse Aggregate, F --- Fibre, M --- Microsilica

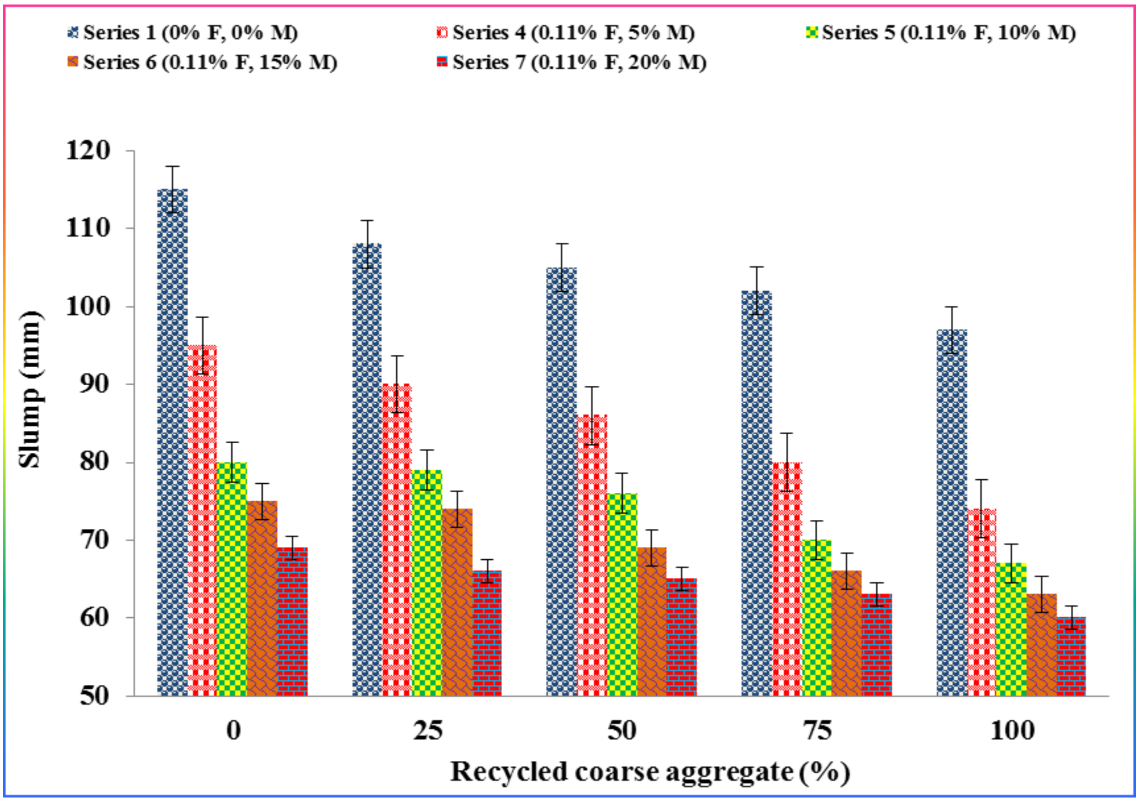
6.2 Slump test

Table 43 displayed the results of workability test for each of the concrete mix incorporating 0, 5, 10, 15, and 20% mineral admixture (microsilica) respectively. A general pattern in reduction was observed as the percentage substitution of natural coarse aggregate by recycled coarse aggregate increased. Workability reduced below the initial specified slump value in Series 4-7 concrete mixes as the percentage addition of microsilica increased. The reduction in workability was as a result of more water demand attributed to the large surface area of microsilica fine particles which required wetting from the free-water (Neville, 1995). This significantly affects the workability of the concrete owing to the strong cohesiveness of the concrete mix resulting in little bleeding. However, these reductions in workability were mitigated through the use of Alphaflow 420 superplasticiser in order to maintain the initial specified slump within the range of 60-180mm.

Table 43: Result of slump test for Series 1, 4, 5, 6, & 7 concrete mix

RCA (%)	Series 1 (0%F, 0%M) (mm)	Series 4 (0.11%F, 5%M) (mm)	Series 5 (0.11%F, 10% M) (mm)	Series 6 (0.11%F, 5% M) (mm)	Series 7 (0.11%F, 20% M) (mm)
0	115	108	105	102	97
25	95	90	86	80	74
50	80	79	76	70	67
75	75	74	69	66	63
100	69	66	65	63	60

RCA --- Recycled Coarse Aggregate, F --- Fibre, M --- Microsilica



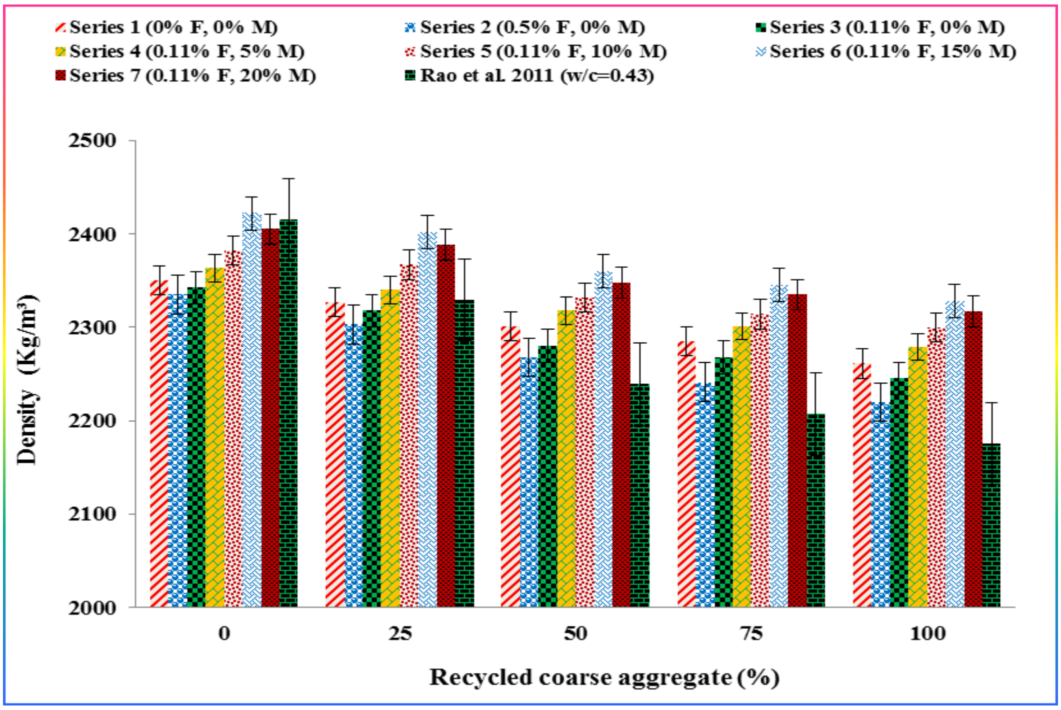
RCA --- Recycled Coarse Aggregate, F --- Fibre, M --- Microsilica

Figure 86. Influence of microsilica on workability of recycled aggregate concrete

Figure 86 illustrates the declining trend in workability as the percentage content of recycled coarse aggregate and micro silica increases respectively. It was observed that higher dosages of Alphaflow 420 superplasticer were required as the percentage addition of microsilica increases from 0%-20% in the concrete mix in order to achieve the specified slump. Results of reduction in slump with higher incorporation of microsilica in the concrete mix was corroborated by Mazloom et al. (2004) and Rao.Hunchate et al. (2014) respectively. The higher water absorption rate associated with recycled coarse aggregate due to adhered mortar and synthetic macro fibre, were also catalysts for these reductions in workability. Previous researchers (Topcu and Şengel (2004); Etxeberria et al. (2007a); Zaidi (2009); Patil et al. (2013)) reported similar findings.

6.3 Density of Concrete

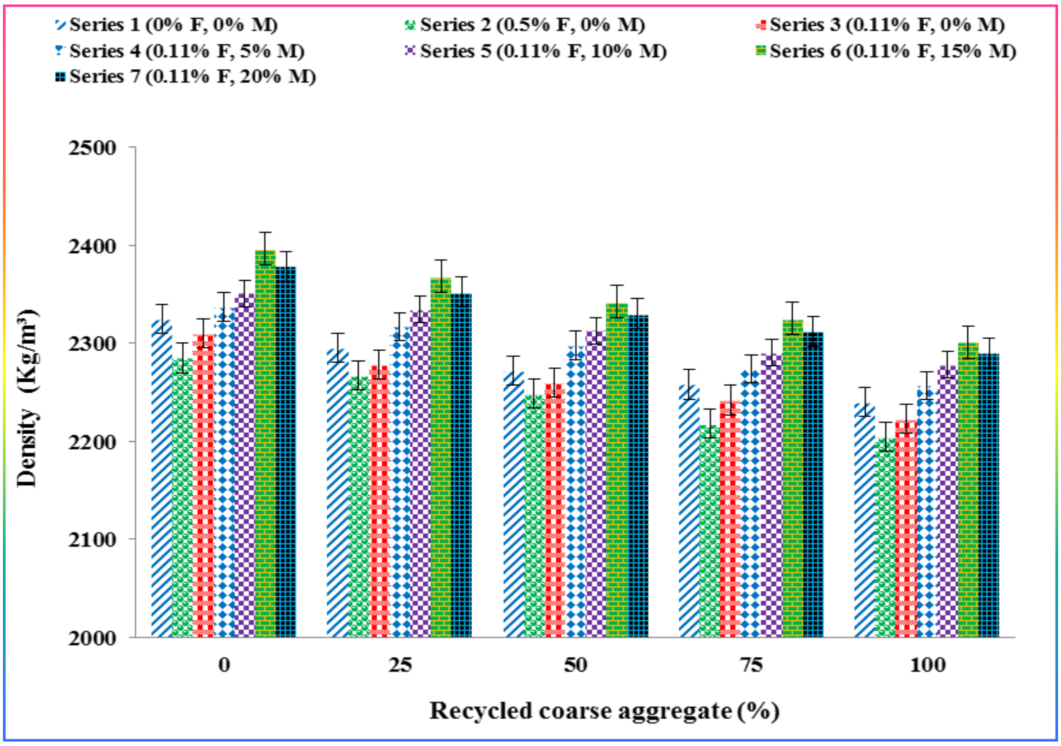
Figures 87 and 88 illustrates the results of fresh concrete density and hardened concrete cube density recorded for each of the concrete mix incorporating 0%, 25%, 50%, 75%, and 100% recycle coarse aggregate respectively in Series 1 - 7.



RCA --- Recycled Coarse Aggregate, F --- Fibre, M --- Microsilica

Figure 87: Variation in fresh concrete density with recycled coarse aggregate contents

Figures 87 and 88 indicates that the density of concrete decreases with increasing content of recycled coarse aggregate in all the mixes. The reason for this observation is due to the light weight and porous nature of recycled coarse aggregate as reported by . Rao et.al., (2011). Series 6 concrete mix with 0.11% fibre and 15% microsilica produced the highest densities in both cases, while concrete mix in Series 2 with 0.5% synthetic macro fibre had the least densities. The densifying effect of microsilica is responsible for this observation.

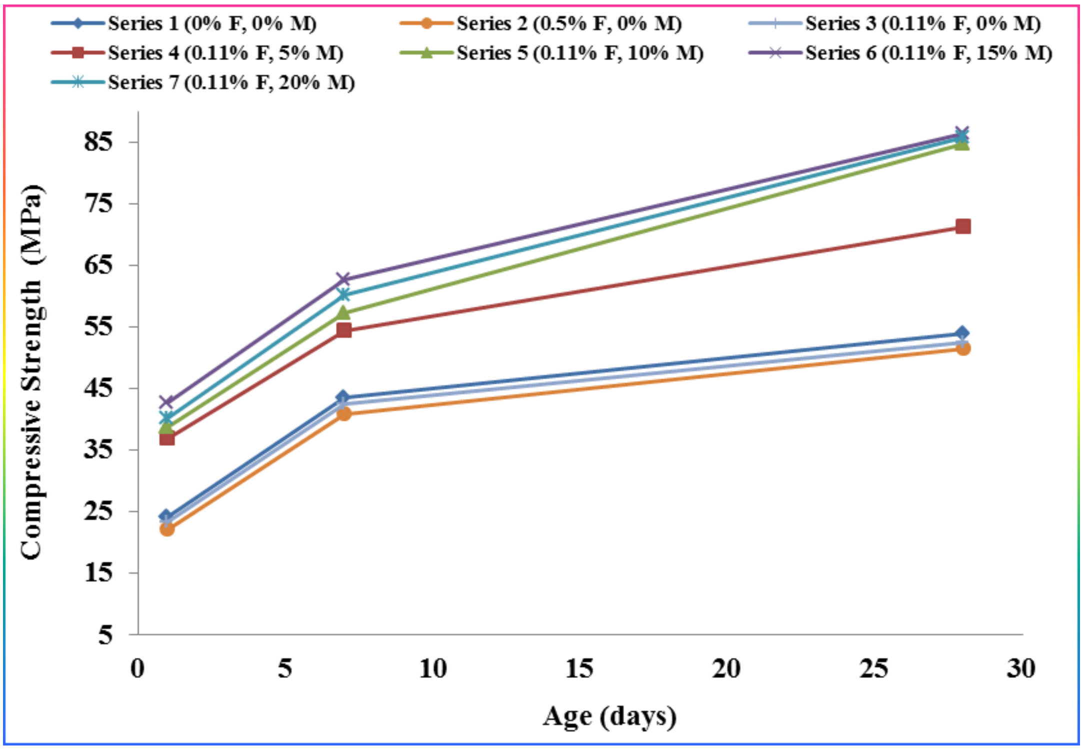


RCA --- Recycled Coarse Aggregate, F --- Fibre, M --- Microsilica

Figure 88: Variation in hardened concrete cube density with recycled coarse aggregate contents

6.4 Compressive strength test

Figures 89 - 93 presents 1, 7, and 28-day compressive cube strength results of concrete mixes in Series 1, 4, 5, 6, and 7 respectively at various percentage replacement of natural coarse aggregate by recycled coarse aggregate. The compressive strengths of concrete mix in Series 6, which incorporates 15% microsilica, had the highest result of compressive cube strength relative to other corresponding concrete mixes in Series 1, 4, 5 and 7 respectively.

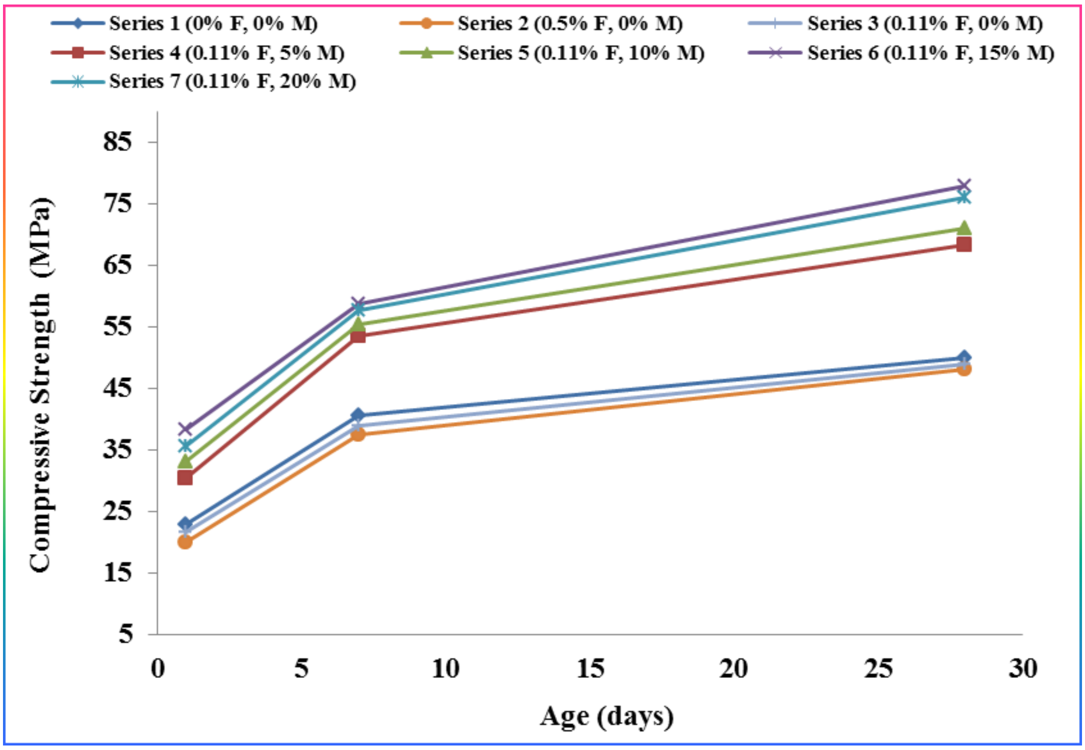


RCA --- Recycled Coarse Aggregate, F --- Fibre, M --- Microsilica

Figure 89. Compressive cube strength at 0% recycled coarse aggregate content

Figure 89 present the results of compressive cube strength for concrete mixes in Series 1, 4, 5, 6, and 7 at 0% recycled coarse aggregate content in the mix. The plot shows that at 28-day curing age, the corresponding compressive cube strengths for Series 1, 4, 5, 6 and 7 concrete mixes were 53.9MPa, 71.2MPa, 84.8MPa, 86.5MPa, and 85.82MPa respectively. With the exception of concrete mix in Series 1 (control), all the concrete mix in Series 4-7 had 28-day compressive cube strength which exceeds the design mix 28-day characteristic cube strength of 50MPa and target compressive cube strength of 63.1MPa. The relative compressive cube strength gained by concrete mix in Series 4-7 with reference to the corresponding mixes in Series 1 were 32.1%, 57.5%, 60.5% and 59.3% respectively. This implies that Series 4-7 concrete mixes incorporated with microsilica produced better results than Series 1.

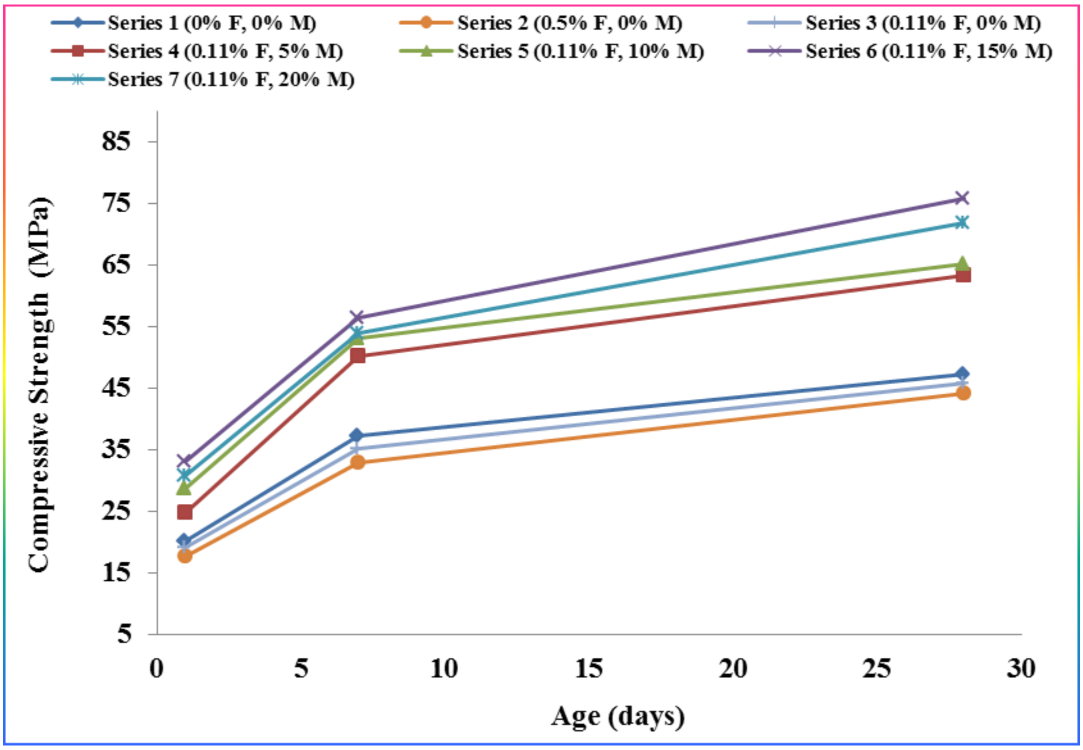
The immense contribution of microsilica in strength development of concrete mix in Series 4-7 could be traced to microsilica's action as a micro filler due to the extreme fineness of the particles (about 100 times smaller than particle size of cement). This improved the parking arrangement of the particles and the interfacial zone between the aggregate and cement paste. The pozzolanic action of microsilica with calcium hydroxide also enhanced the early age strength development of concrete mix in Series 4-7. Series 7 with 20% micro silica addition had relative strength reduction of about 0.74% compared with concrete mix in Series 6 which incorporates 15% micro silica content.



RCA --- Recycled Coarse Aggregate, F --- Fibre, M --- Microsilica

Figure 90. Compressive cube strength at 25% recycled coarse aggregate content

Figure 90 illustrate the results of 1, 7, and 28-day compressive cube strength of concrete mixes in Series 1, 4, 5, 6, and 7 respectively at 25% recycled coarse aggregate content. The plot shows that the 28-day compressive cube strength of concrete mix in all the Series were 50.1MPa, 68.4MPa, 71MPa, 77.9MPa, and 75.9MPa respectively. The relative compressive cube strength increase in Series 4, 5, 6, and 7 concrete mix relative to Series 1 at 28-day curing age were 36.6%, 41.8%, 55.5%, and 51.6% respectively. The relative compressive cube strength reduction in Series 7 relative to Series 6 at 28-day curing age was 2.49%. Excluding concrete mix in Series 1 (control), all other concrete mix in Series 4-7 produced 28-day compressive cube strength which exceeds the design mix 28-day characteristic cube strength of 50MPa and target compressive cube strength of 63.1MPa.

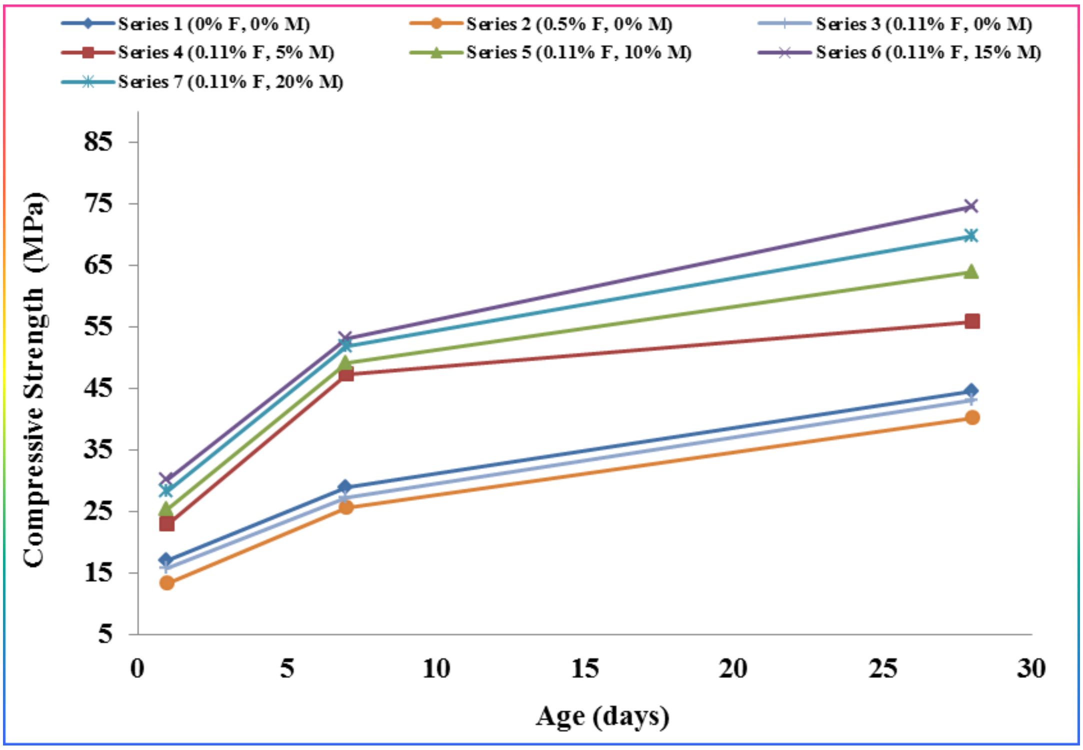


RCA --- Recycled Coarse Aggregate, F --- Fibre, M --- Microsilica

Figure 91. Compressive cube strength at 50% recycled coarse aggregate content

Figures 91 and 92 illustrate the results of 1, 7, and 28-day compressive cube strength for concrete mixes in Series 1, 4, 5, 6, and 7 at 50% and 75% recycled coarse aggregate content respectively. The increase in 28-day compressive cube strength of concrete mixes in Series 4-7 were 34.2%, 38%, 60.3%, and 52.1% respectively, relative to the

28-day compressive cube strength of concrete mixes in Series 1. Similar strength increase of about 25.5%, 43.7%, 67.4%, and 56.5% respectively were recorded in Series 4-7 relative to Series 1 at 75% recycled coarse aggregate content. The relative compressive cube strength reduction in Series 7 concrete mix with 50% and 75% recycled coarse aggregate content relative to Series 6 at 28-day were 5.37% and 6.96% respectively. The 28-day compressive cube strength of Series 4-7 concrete mix at 50% recycled coarse aggregate content exceeded the design mix 28-day characteristics compressive cube strength of 50MPa and target mean strength of 63.1MPa compared with Series 1 mix. This implies that the substitution of 50% natural coarse aggregate with recycled coarse aggregate does not adversely affect the strength of the concrete.

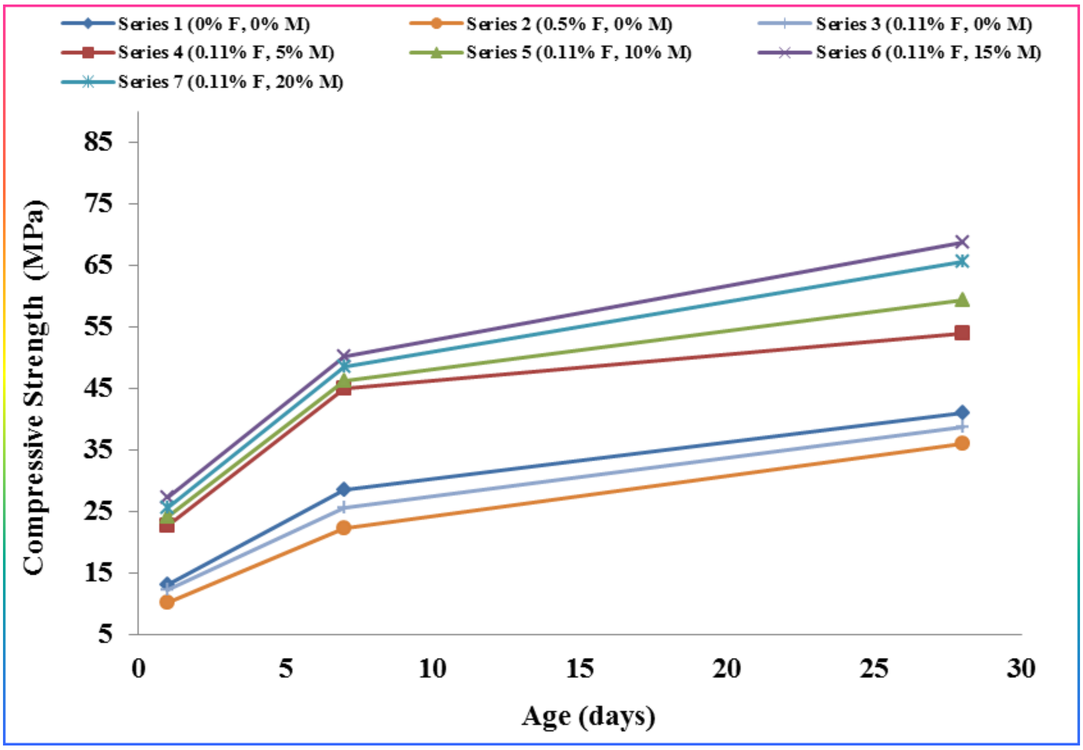


RCA --- Recycled Coarse Aggregate, F --- Fibre, M --- Microsilica

Figure 92. Compressive cube strength at 75% recycled coarse aggregate content

At 75% recycled aggregate content, Series 5-7 exceeded the 28-day characteristics compressive cube strength and target mean compressive cube strength of 50MPa and

63.1MPa respectively while Series 4 mix only exceeds the 28-day characteristics strength but fell below the target mean compressive strength. This implies that 75% recycled coarse aggregate had little or no significant on Series 5-7 concrete mix.



RCA --- Recycled Coarse Aggregate, F --- Fibre, M --- Microsilica

Figure 93. Compressive cube strength at 100% recycled coarse aggregate content

Figure 93 depict results of 1, 7, and 28-day compressive cube strength of concrete mixes in Series 1, 4, 5, 6, and 7 respectively at 100% substitution of natural coarse aggregate by recycled coarse aggregate. The chart shows that relative to Series 1 concrete mix, the strength gain by Series 4-7 concrete mixes were 31.5%, 44.6%, 67.8% and 59.9% respectively. Series 6 and 7 which incorporates 15% and 20% recycled coarse aggregate respectively exceeded both 28-day design mix characteristics compressive cube strength of 50MPa and target mean compressive cube strength of 63.1MPa respectively. Series 4 and 5 also exceeded the 28-day characteristics design mix compressive cube strength but fell below the target mean compressive strength. The implication is that the replacement of natural coarse aggregate by recycled coarse aggregate has no significance on concrete mixes in Series 6 and 7 while the impact on Series 4 and 5 is low compared with Series 1 concrete mix. Series 7 concrete mix at 28-day compressive cube strength had relative reduction of about 4.94% compared with Series 6 concrete mix.

The significant results in Series 4-7 concrete mixes which incorporates microsilica attest to the appreciative pozzolanic efficiency of microsilica through its densifying action. The incorporation of 15% microsilica in Series 6 concrete mix produced the best strength improvement compared to other mixes, while further addition result in strength reduction as indicated in compressive strength of concrete mixes in series 7 incorporating 20% microsilica addition. The compressive cube strength was influenced by both pozzolanic and micro filler effect of microsilica in conjunction with the synergies between aggregate and cement matrix thereby leading to the creation of less porous and better interlocking between them.

The reduction in compressive cube strength of concrete mix in Series 7 with higher microsilica content occurred due to the excess amount of small sized microsilica particles. These drifts the cement grains to one side and caused unpacking of the entire system and eventually lead to significant reduction in the strength of the concrete (Neville, 1995). Rao.Hunchate et al. (2014), revealed that increasing micro silica content in a concrete mix up to 15% effectively increased the compressive strength while further addition reduced the strength. Yogendran et al. (1987) and Annadurai and Ravichandran (2014) reported that 28-day compressive cube strength increased between

50-70 MPa with the addition of microsilica, and the optimal benefits was derived at 15% micro silica content. Generally, the compressive strength decreases with increase in recycled coarse aggregate content in the mix although this effect was minimised by micro silica. The results from Series 4-7 shows that contrary to the recommended use of recycled aggregate in concrete mix at 30% (BSI, 2000), there is a great potential to increase the use of recycled coarse aggregate from 30% to 50% by incorporating 5-15% micro silica in the concrete mix with the best results achieved with 15% addition. Figures 94 – 98 displayed various failure patterns of concrete cubes identified during compressive cube strength test.

(a) Series 2 (0.5% F, 0% M)

(b) Series 3 (0.11% F, 0% M)

(c) Series 4 (0.11% F, 5% M)

(d) Series 5 (0.11% F, 10% M)

(e) Series 6 (0.11% F, 5% M)

(f) Series 7 (0.11% F, 10% M)

Figure 94. Failure patterns of cube specimens at 28-days compression test (0% RCA)

(a) Series 2 (0.5% F, 0% M)

(b) Series 3 (0.11% F, 0% M)

(c) Series 4 (0.11% F, 5% M)

(d) Series 5 (0.11% F, 10% M)

(e) Series 6 (0.11% F, 15% M)

(f) Series 7 (0.11% F, 20% M)

Figure 95. Failure patterns of cube specimens at 28-days compression test (25% RCA)

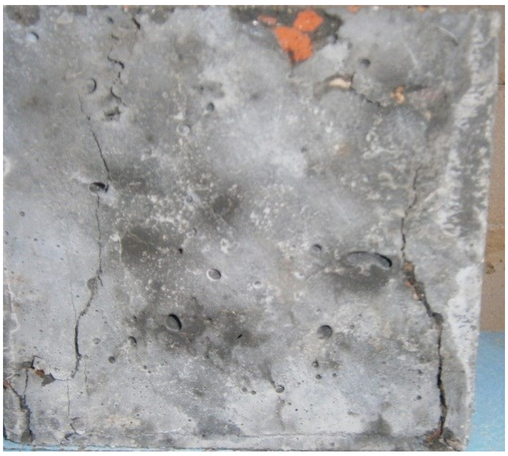
(a) Series 2 (0.5% F, 0% M)

(b) Series 3 (0.11% F, 0% M)

(c) Series 4 (0.11% F, 5% M)

(d) Series 5 (0.11% F, 10% M)

(e) Series 6 (0.11% F, 15% M)



(f) Series 7 (0.11% F, 20% M)

Figure 96. Failure patterns of cube specimens at 28-days compression test (50% RCA)

(a) Series 2 (0.5% F, 0% M)

(b) Series 3 (0.11% F, 0% M)

(c) Series 4 (0.11% F, 5% M)

(d) Series 5 (0.11% F, 10% M)

(e) Series 6 (0.11% F, 15% M)

(f) Series 7 (0.11% F, 20% M)

Figure 97. Failure patterns of cube specimens at 28-days compression test (75% RCA)

(a) Series 2 (0.5% F, 0% M)

(b) Series 3 (0.11% F, 0% M)

(c) Series 4 (0.11% F, 5% M)

(d) Series 5 (0.11% F, 10% M)

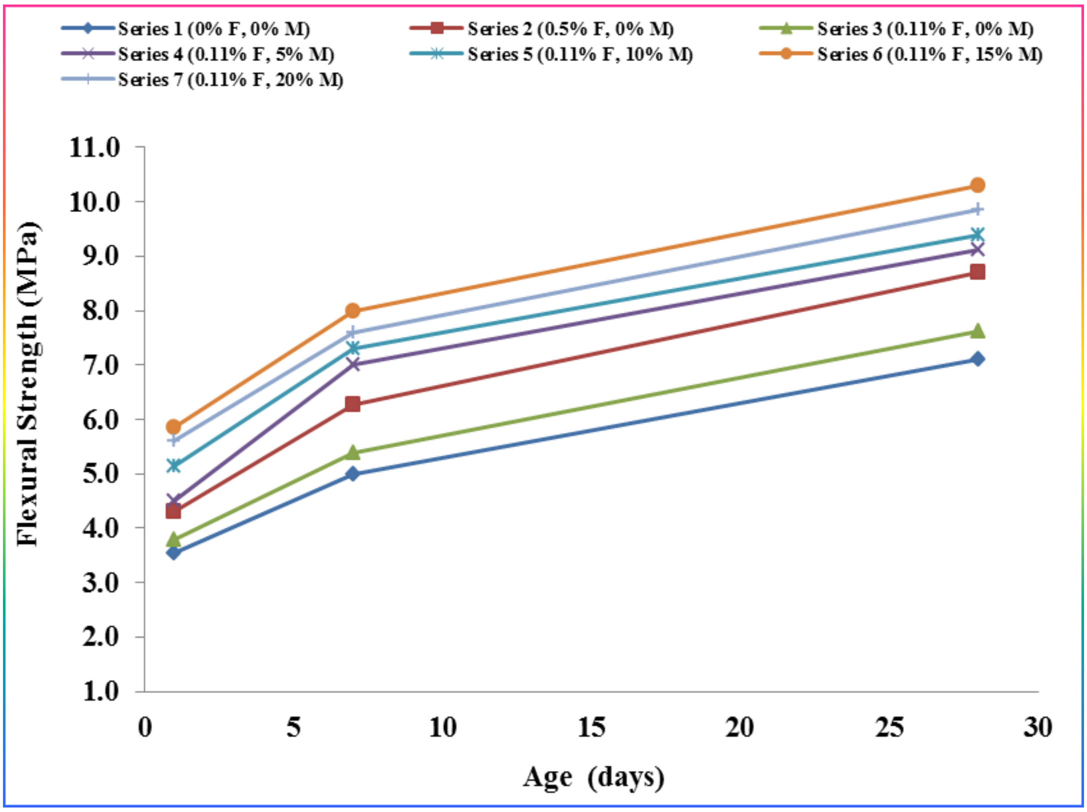
(e) Series 6 (0.11% F, 15% M)

(f) Series 7 (0.11% F, 20% M)

Figure 98. Failure patterns of cube specimens at 28-days compression test (100% RCA)

6.5 Flexural strength test

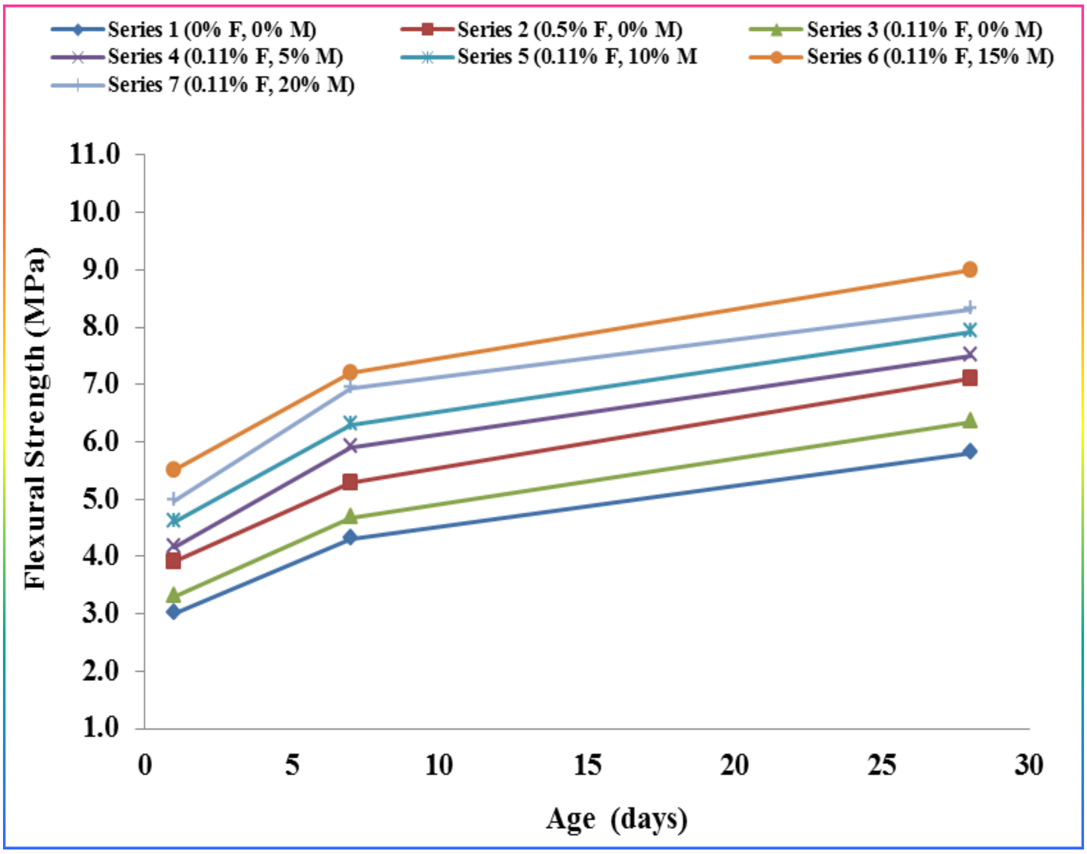
Figures 99 -103 illustrates 1, 7, and 28-day flexural strength of all the concrete mixes for Series 1, 4, 5, 6 and 7 respectively. The flexural strength of concrete mixes in Series 4-7 had higher flexural strength results than the corresponding control concrete mix in Series 1. The maximum relative strength increase occurred in Series 6, which incorporates 15% microsilica addition. This was due to the improved microstructure of the interfacial transition zone as a result of the connection between recycled coarse aggregate, natural coarse aggregate and the new cement matrix influenced by microsilica.



RCA --- Recycled Coarse Aggregate, F --- Fibre, M --- Microsilica

Figure 99. Flexural strength at 0% recycled coarse aggregate content

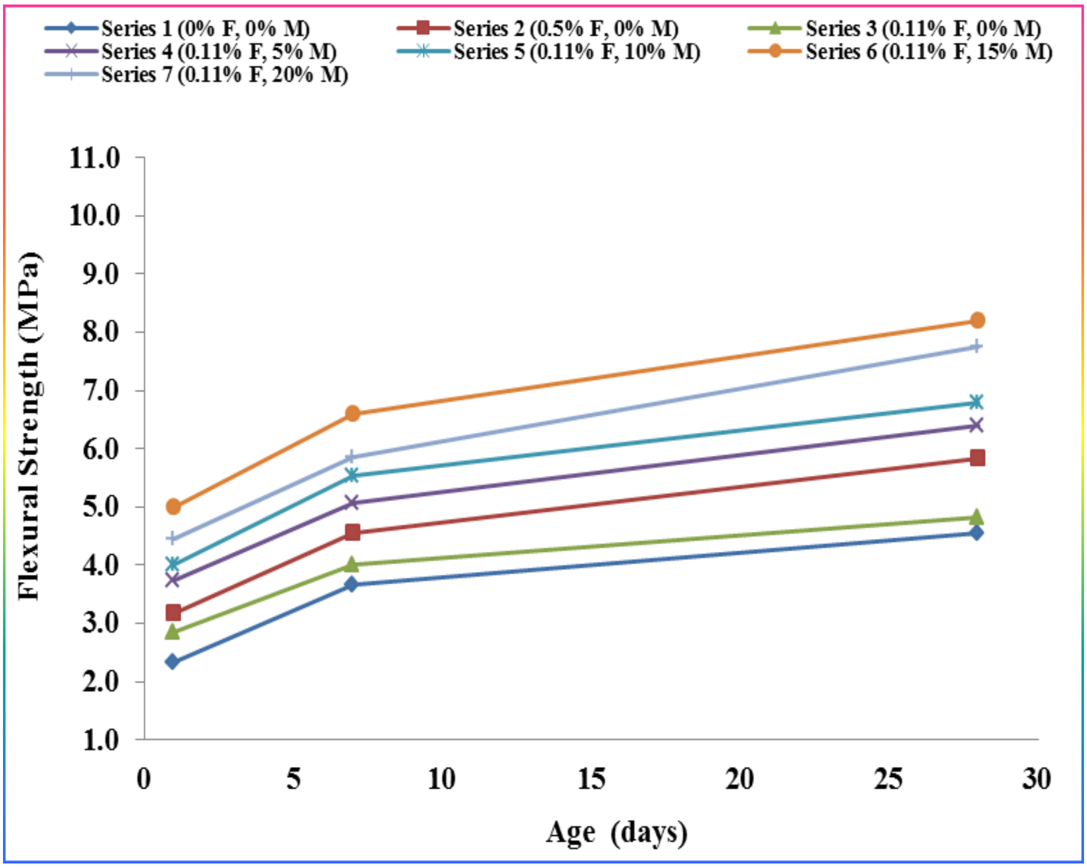
Figure 99 illustrate results of flexural strength for concrete mixes in Series 1, 4, 5, 6, and 7 at 0% recycled coarse aggregate content in the mix. The plot shows that at 28-day curing age, the corresponding flexural strengths for Series 1, 4, 5, 6 and 7 concrete mixes were 7.10MPa, 9.13MPa, 9.40MPa, 9.85MPa, and 10.30MPa respectively. The relative flexural strength gained by concrete mix in Series 6 with reference to the corresponding mixes in Series 1, 4, 5, and 7 were 45.1%, 12.8%, 9.57% and 4.57% respectively. This implies that Series 6 concrete mixes incorporated with microsilica produced better results than any other mix.



RCA --- Recycled Coarse Aggregate, F --- Fibre, M --- Microsilica

Figure 100. Flexural strength at 25% recycled coarse aggregate content

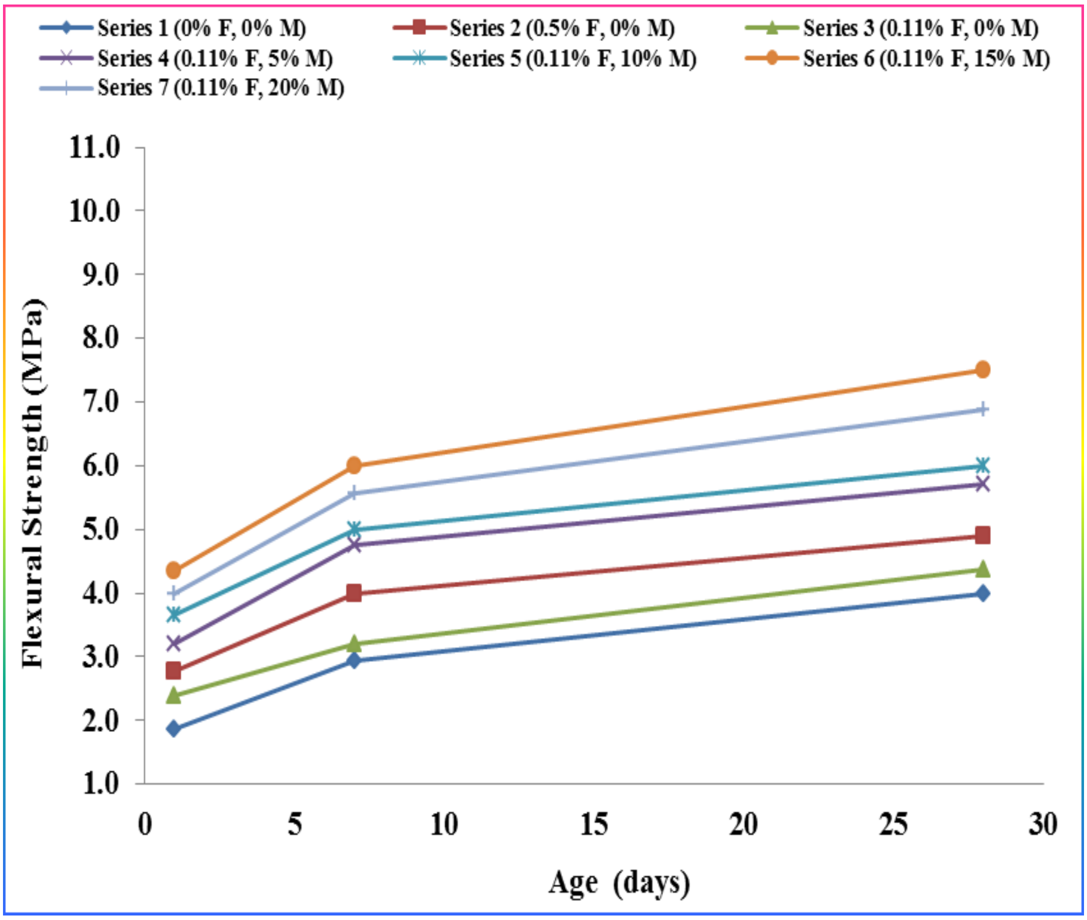
Figure 100 depict the results of 1, 7, and 28-day flexural strength of concrete mixes in Series 1, 4, 5, 6, and 7 respectively at 25% recycled coarse aggregate content. The plot shows that the 28-day flexural strength of concrete mix in all the Series were 5.80MPa, 7.50MPa, 7.92MPa, 8.30MPa, and 9.00MPa respectively. The relative flexural strength increase in Series 6 concrete mix relative to Series 1, 4, 5 and 7 at 28-day curing age were 55.2%, 20%, 13.6%, and 8.4% respectively. The relative compressive cube strength reduction in Series 7 relative to Series 6 at 28-day curing age was 2.49%. Excluding concrete mix in Series 1 (control), all other concrete mix in Series 4-7 produced 28-day compressive cube strength which exceeds the design mix 28-day characteristic cube strength of 50MPa and target compressive cube strength of 63.1MPa.



RCA --- Recycled Coarse Aggregate, F --- Fibre, M --- Microsilica

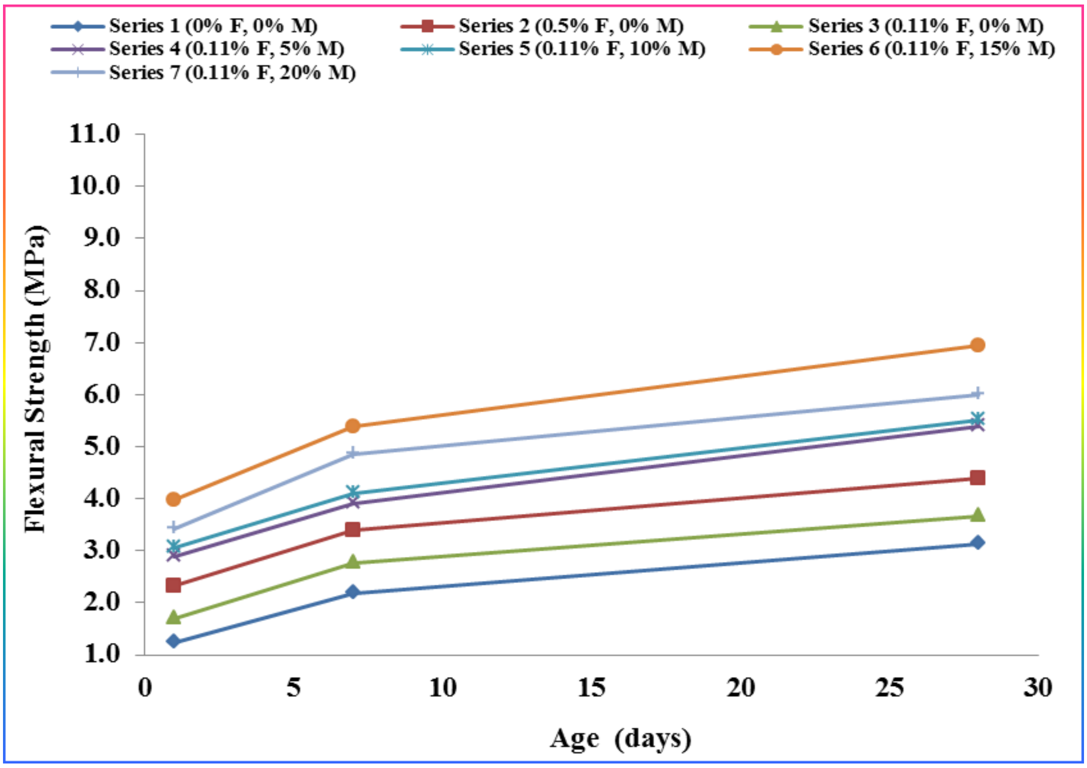
Figure 101. Flexural strength at 50% recycled coarse aggregate content

Figures 101 and 102 represent results of 1, 7, and 28-day flexural strength for concrete mixes in Series 1, 4, 5, 6, and 7 at 50% and 75% recycled coarse aggregate content respectively. The increase in 28-day flexural strength of concrete mixes at 50% recycled coarse aggregate content in Series 6 relative to the corresponding mixes in Series 1, 4, 5, and 7 respectively were 80.2%, 28.1%, 20.6%, and 5.81% respectively. Similar strength increase of about 87.5%, 31.6%, 25.0%, and 9.0% respectively were recorded in Series 6 concrete mix relative to Series 1, 4, 5, and 7 respectively at 75% recycled coarse aggregate content.



RCA --- Recycled Coarse Aggregate, F --- Fibre, M --- Microsilica

Figure 102. Flexural strength at 75% recycled coarse aggregate content

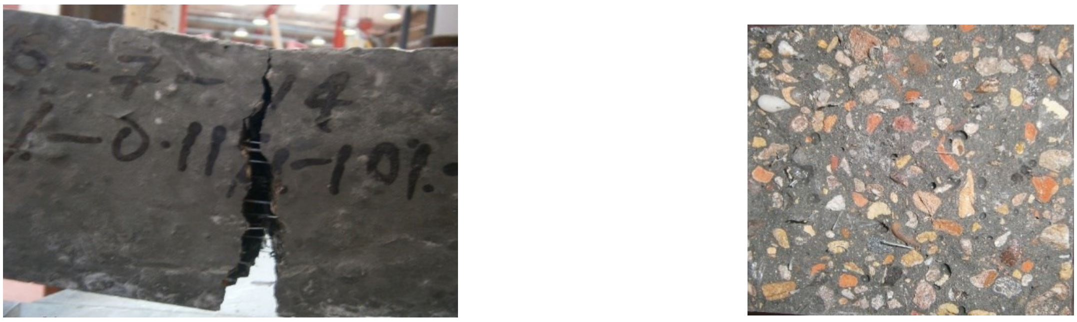


RCA --- Recycled Coarse Aggregate, F --- Fibre, M --- Microsilica

Figure 103. Flexural strength at 100% recycled coarse aggregate content

Figure 103 expressed the results of 1, 7, and 28-day flexural strength of concrete mixes in Series 1, 4, 5, 6, and 7 respectively at 100% substitution of natural coarse aggregate by recycled coarse aggregate. The graph shows that relative to Series 6 concrete mixes, the flexural strength reduction of concrete mixes in Series 1, 4, 5, and 7 respectively were 45%, 22.2%, 20.5%, and 13.5% respectively. There were large variance between flexural strength results obtained from concrete mix in Series 1 and Series 4-7 respectivley at any given recycled coarse aggregate content. These observations attest to the effectiveness and efficiency of microsilica to enhance the performance of the concrete. The impact of microsilica in Series 6 concrete mixes was very significant compared with the flexural strength obtained in series 1, 4, 5, and 7 respectively. Bhanja and Sengupta (2005), reported significant improvement in flexural strengths of concrete mixes incorporating micro silica, and also noted that the optimum improvement occurred in concrete mix with 15% microsilica addition. Figure 104 shows various failure modes observed from flexural strength test.

(a) Series 4 (0.11% F, 5% M)



(b) Series 5 (0.11% F, 10% M)

(c) Series 6 (0.11% F, 15% M)

(d) Series 7 (0.11% F, 10% M)

Figure 104. Failure patterns of cube specimens at 28-days compression test (100% RCA)

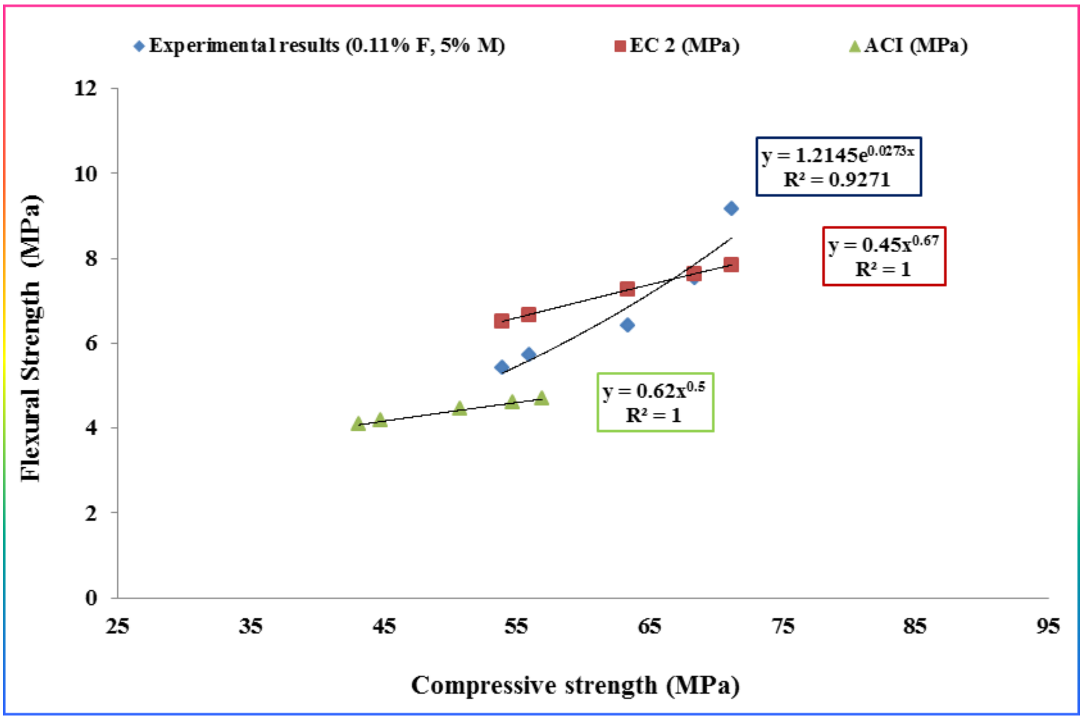
6.6 Correlation between Flexural strength and compressive strength

The comparison of actual results of compressive and flexural strength obtained from the experiment against the empirical values from predictive equations given in EC-2 and ACI-318M are given in Table 44 and Figure 105 respectively

Table 44: Experimental and predictive flexural strength- Series 4 (0.11% F, 5% M)

RCA (%)	Experimental Compressive strength		Predicted Flexural strength		Experimental Flexural strength (MPa)
	fck, cube (MPa)	fck, cyl. (MPa)	EC 2 (MPa) $\{f_{ct,fl} = 0.45f_{ck}^{(2/3)}\}$	ACI (MPa) $\{f_r = 0.62\sqrt{fck'}\}$	
0	71.15	56.92	7.84	4.68	9.13
25	68.40	54.72	7.63	4.59	7.50
50	63.40	50.72	7.25	4.42	6.40
75	55.90	44.72	6.67	4.15	5.70
100	53.90	43.12	6.51	4.07	5.40

It was observed that EC-2 slightly underestimate the flexural strength of concrete mix without recycled coarse aggregate, fibre and microsilica. However, EC-2 slightly over-estimated the flexural strength of concrete mixes incorporating 25%, 50%, 75%, and 100% recycled coarse aggregate respectively. On the other hand, ACI significantly underestimate the flexural strength of all the concrete mixes. The relationship between flexural strength and compressive strength was assessed in order to ascertain the nature of their correlation. The regression analysis indicate that an exponential relationship exists between flexural and compressive strength as $\mathbf{f_{ct,fl} = 1.21e^{0.03fck}}$ with a correlation coefficient $\mathbf{R^2 = 0.93}$.



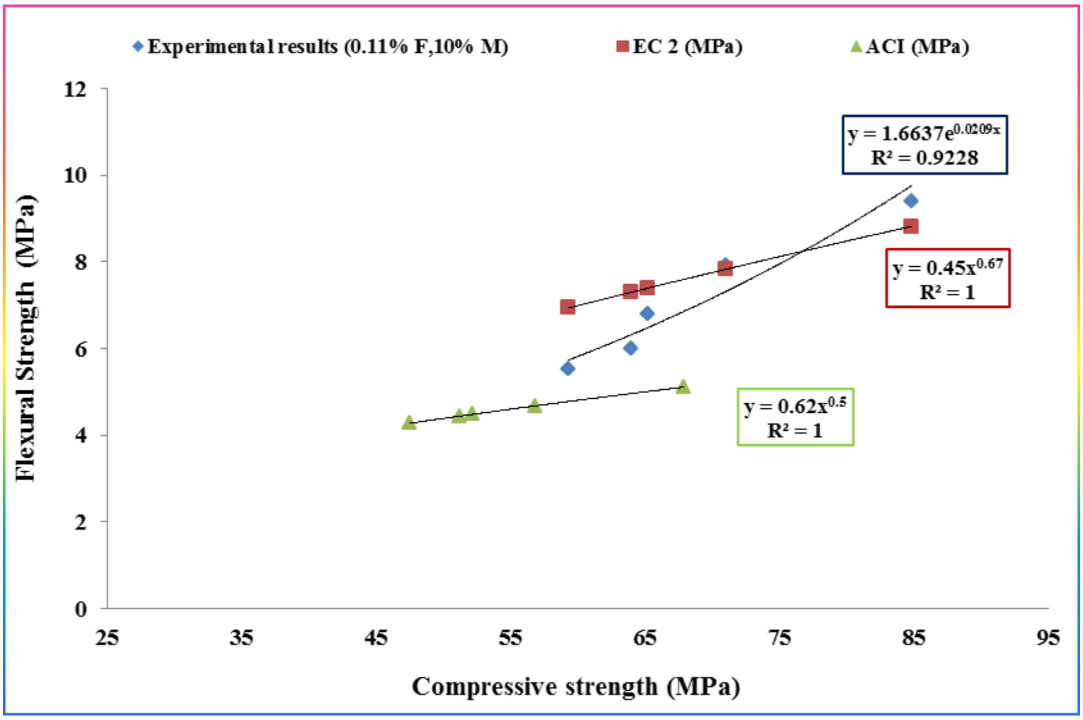
F --- Fibre, M --- Microsilica

Figure 105. Relationship between Flexural strength and compressive strength

Results from Table 45 indicate that, the experimental flexural strength of concrete mixes with 0% and 25% recycled aggregate are higher than the predictive values obtained from EC-2 while the flexural strength of mixes with 50%, 75%, and 100% recycled aggregate were slightly overestimated by EC-2. Predictive equation from ACI significantly underestimate the flexural strength of all the mixes in Series 5. The relationship between flexural and compressive strength assume an exponential relationship $\mathbf{f_{ct,fl} = 1.66e^{0.02fck}}$ with a correlation coefficient $\mathbf{R^2 = 0.92}$.

Table 45: Experimental and predictive flexural strength Series 5 (0.11% F, 10% M)

RCA (%)	Experimental Compressive strength		Predicted Flexural strength		Experimental Flexural strength (MPa)
	fck, cube (MPa)	fck, cyl. (MPa)	EC 2 (MPa) $\{f_{ct,fl} = 0.45f_{ck}^{(2/3)}\}$	ACI (MPa) $\{f_r = 0.62\sqrt{fck'}\}$	
0	84.84	67.87	8.82	5.11	9.40
25	71.00	56.80	7.83	4.67	7.92
50	65.20	52.16	7.39	4.48	6.80
75	63.98	51.18	7.30	4.44	6.00
100	59.30	47.44	6.94	4.27	5.52



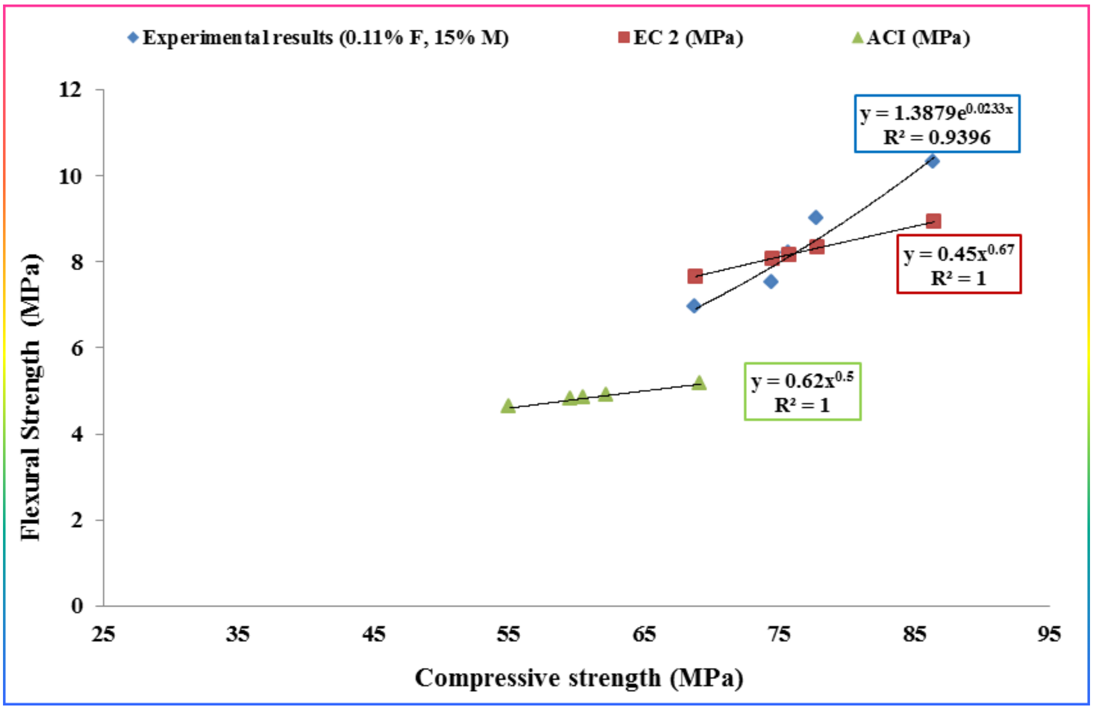
F --- Fibre, M --- Microsilica

Figure 106. Relationship between Flexural strength and compressive strength

Table 46: Experimental and predictive flexural strength Series 6 (0.11% F, 15% M)

RCA (%)	Experimental Compressive strength		Predicted Flexural strength		Experimental Flexural strength (MPa)
	fck, cube (MPa)	fck, cyl. (MPa)	EC 2 (MPa) $\{f_{ct,fl} = 0.45f_{ck}^{(2/3)}\}$	ACI (MPa) $\{f_r = 0.62\sqrt{fck'}\}$	
0	86.46	69.17	8.93	5.16	10.30
25	77.85	62.28	8.32	4.89	9.00
50	75.74	60.59	8.17	4.83	8.20
75	74.53	59.62	8.08	4.79	7.50
100	68.78	55.02	7.66	4.60	6.94

Table 46 show the results of comparison of compressive and flexural strength obtained from the experiment against the empirical values calculated from predictive equations in EC-2 and ACI-318M, while Figure 107 depicts the exponential relationship between flexural and compressive strength as $\mathbf{f_{ct,fl} = 1.39e^{0.02fck}}$ with a correlation coefficient $\mathbf{R^2 = 0.94}$. For concrete mixes in Series 6 with 0%, 25%, and 50% recycled aggregate content, EC-2 underestimate the flexural strength. However, the flexural strength of mixes incorporating 75% and 00% recycled aggregate were over estimated by EC-2. The predictive equation by ACI significantly underestimated the flexural strength of all the mixes in Series 6.



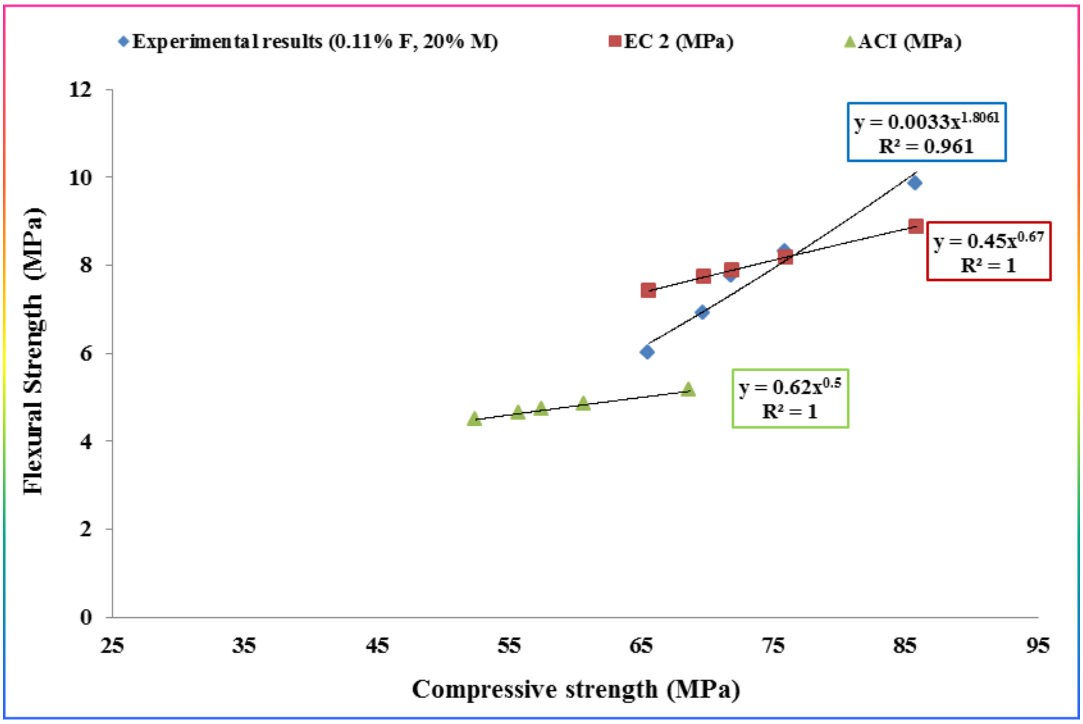
F --- Fibre, M --- Microsilica

Figure 107. Relationship between Flexural strength and compressive strength

It was observed from Table 47 that, EC-2 underestimate the flexural strength of concrete mixes with 0% and 25% recycled aggregate respectively while the values of concrete mixes with 50% and 100% recycled aggregates were overestimated slightly. On the other hand, ACI completely underestimated the flexural strength of all the mixes in Series 7. The correlation between the flexural and compressive strength from the regression analysis illustrated in Figure 109, produced an exponential relationship of $\mathbf{f_{ct,fl} = 1.33e^{0.02fck}}$ with a correlation coefficient $\mathbf{R^2 = 0.95}$.

Table 47: Experimental and predictive flexural strength Series 7 (0.11% F, 20% M)

RCA (%)	Experimental Compressive strength		Predicted Flexural strength		Experimental Flexural strength (MPa)
	fck, cube (MPa)	fck, cyl. (MPa)	EC 2 (MPa) $\{f_{ct,fl} = 0.45f_{ck}^{(2/3)}\}$	ACI (MPa) $\{f_r = 0.62\sqrt{fck'}\}$	
0	85.82	68.66	8.89	5.14	9.85
25	75.91	60.73	8.18	4.83	8.30
50	71.88	57.50	7.89	4.70	7.75
75	69.68	55.74	7.73	4.63	6.88
100	65.54	52.43	7.42	4.49	6.00

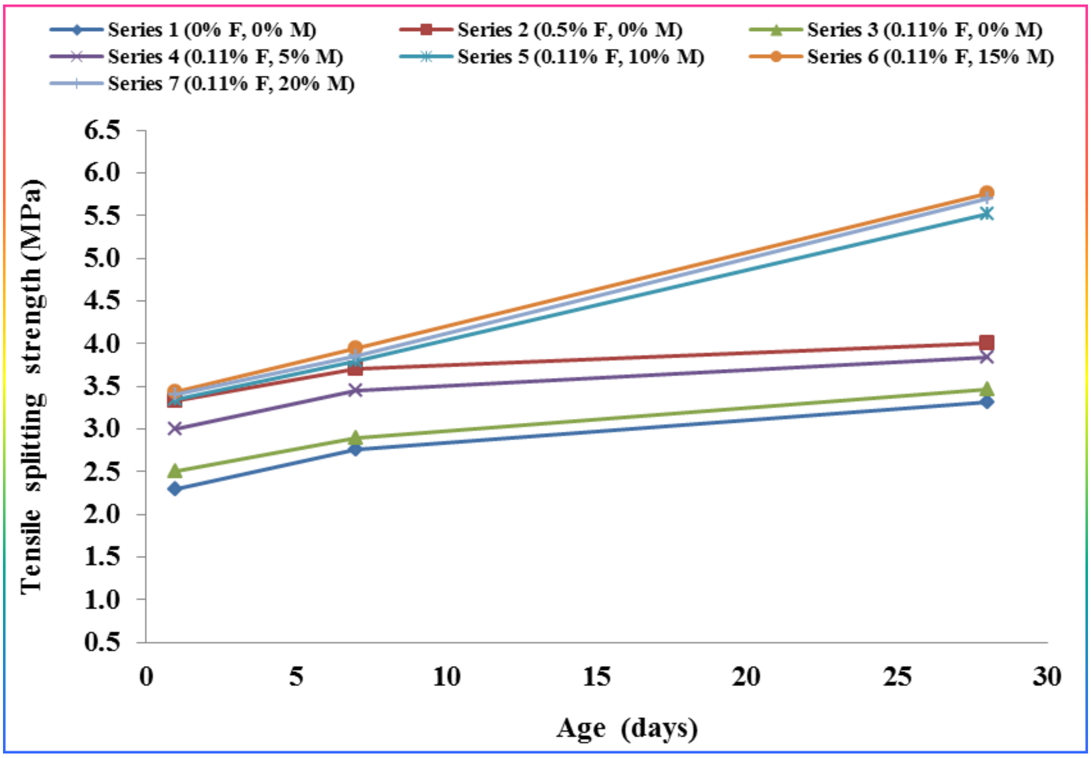


RCA --- Recycled Coarse Aggregate, F --- Fibre, M --- Microsilica

Figure 108. Relationship between Flexural strength and compressive strength

6.7 Tensile splitting strength test

Results of average indirect tensile splitting strength at 1,7 and 28-day curing age for Series 1, 4, 5, 6, and 7 concrete mixes respectively are illustrated in figures 109 -113. The tensile splitting strength decreased with increase in percentage substitution of recycle aggregate in all the concrete mixes.

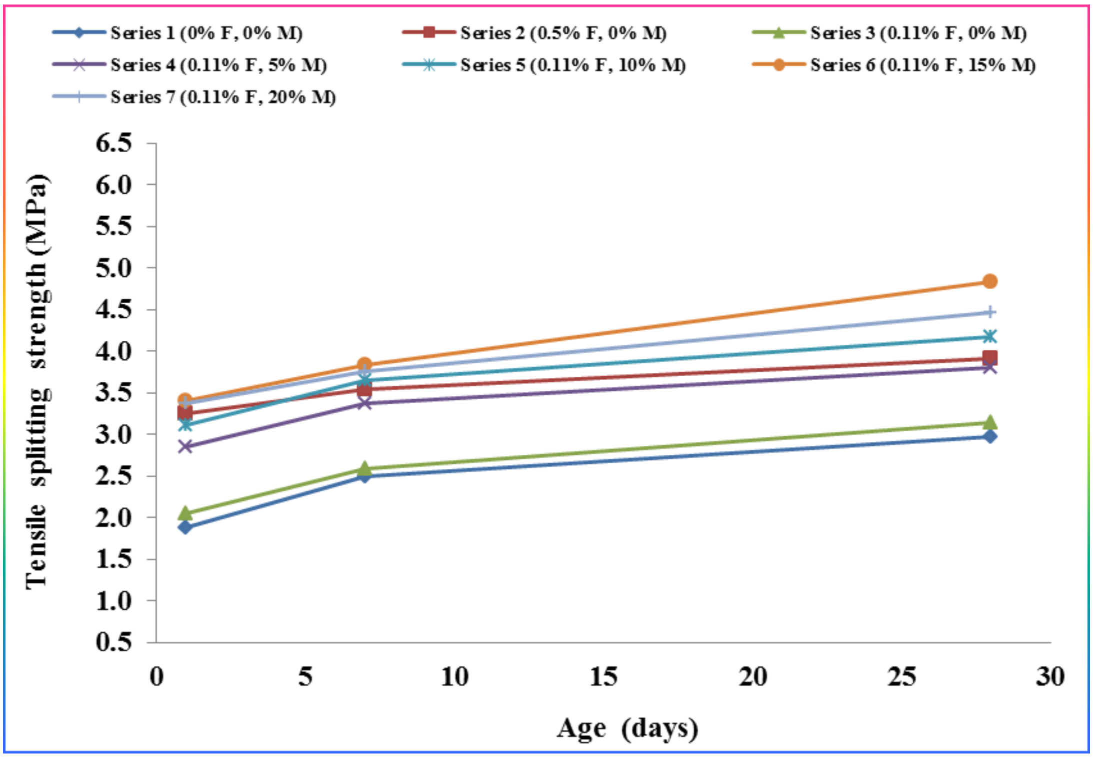


RCA --- Recycled Coarse Aggregate, F --- Fibre, M --- Microsilica

Figure 109. Tensile splitting strength at 0% recycled coarse aggregate content

Figure 109 illustrates results of 1, 7, and 28-day tensile splitting strength for cocnrete mixes in Series 1, 4, 5, 6 and 7 respectively at 0% recycled coarse aggregate content. The plots indicate that concrete mixes in Series 6 which incorporates 15% micro silica content produced results better than concrete mixes in Series 1, 4, 5, and 7 respectively. The 28-day relative tensile splitting strength gained by Series 6 concrete mix relative to

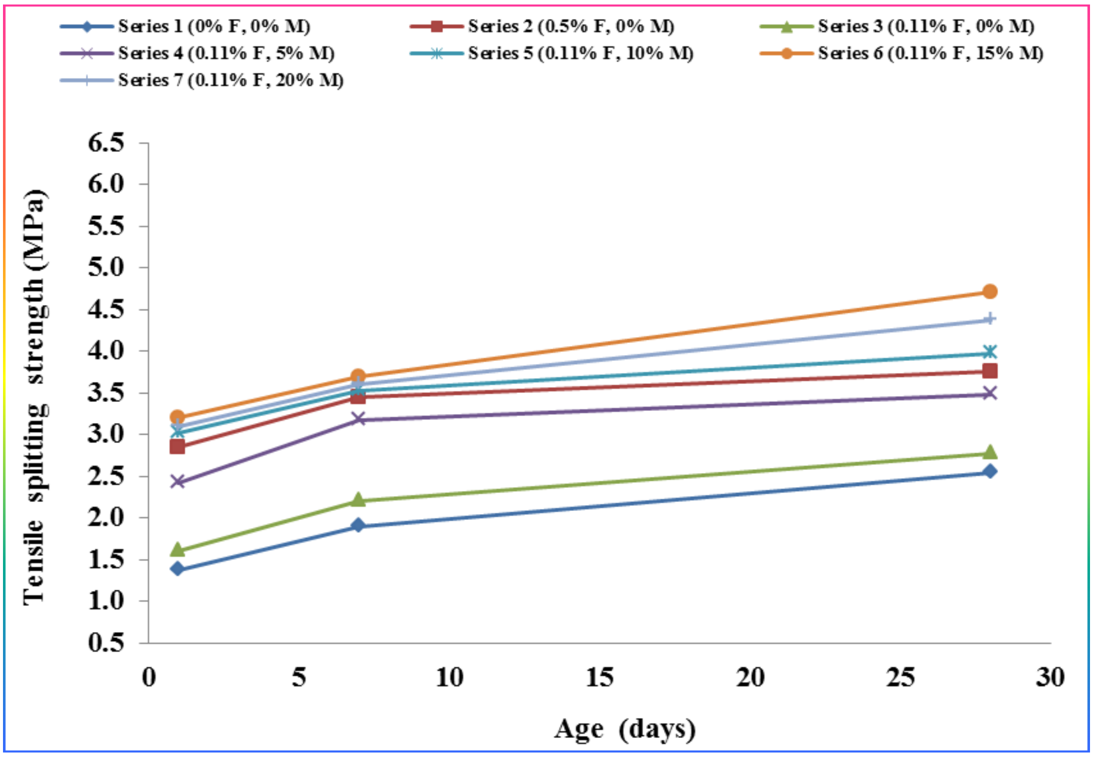
Series 1, 4, 5, and 7 concrete mixes were 73.5%, 50%, 4.35%, and 1.05% respectively. Series 5, 6, and 7 indicate wide disparity in comparison with Series 1 and 4 concrete mix. This implies that tensile splitting strength increases with increasing micro silica content in the mix up till 15% addition beyond which the strength decline.



RCA --- Recycled Coarse Aggregate, F --- Fibre, M --- Microsilica

Figure 110. Tensile splitting strength at 25% recycled coarse aggregate content

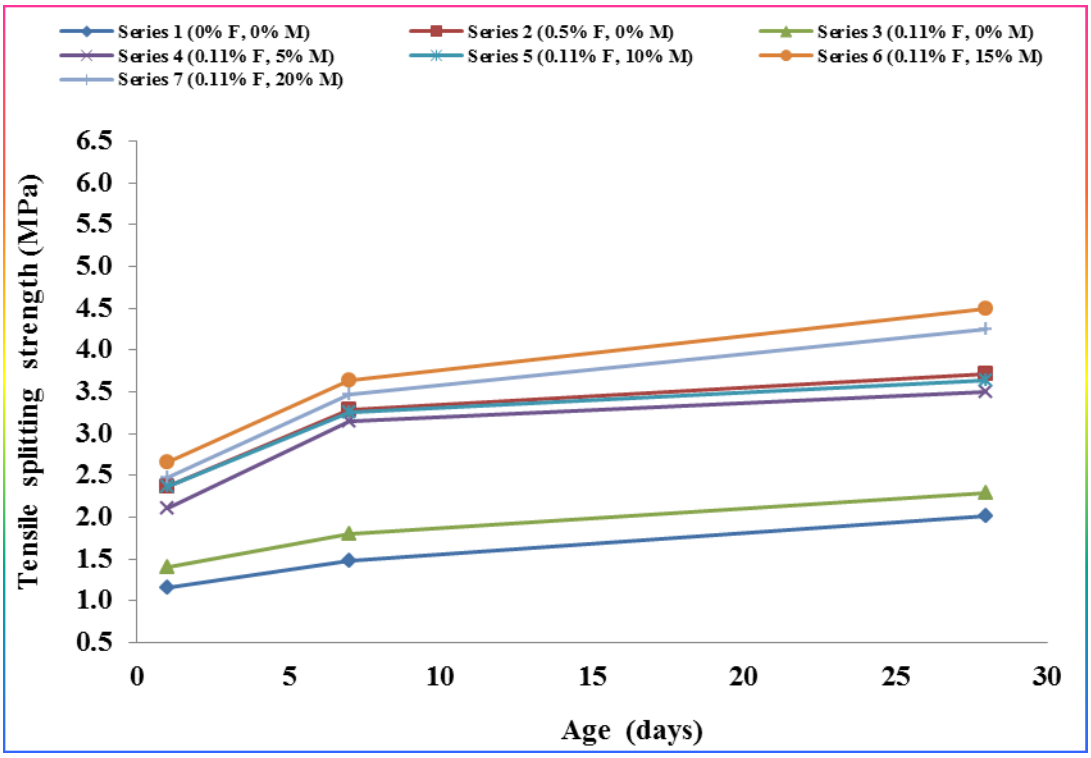
Figure 110 illustrates 1, 7, and 28-day tensile spliting strength results of concrete mix in Series 1, 4, 5, 6, and 7 respectively with 25% recycled coarse aggregate content. The plots shows that Series 6 concrete mix at 28-day curing age had tensile splitting strength of about 62.4%, 27%, 16.1% and 8.3% more than the corresponding mix in Series 1, 4, 5, and 7 respectively. The plots indicate a clear disparity between Series 6 and other Series unlike in figure 112. This implies that the replacement of 25% natural coarse aggregate by recycled coarse aggregate had impacted the tensile splitting strength development. This observation agreed with the strength reduction pattern reported by Evangelista and De Brito (2007) which was attributed to the porous nature of the recycled aggregate. However, concrete mixes in series 4–7 incorporating microsilica produced significant relative strength gains due to improved microstructure of the interfacial transition zone and increased bond strength between the new cement paste and recycled coarse aggregate catalysed by addition of microsilica (Kou et al., 2011). Bhanja and Sengupta (2005), also corroborates this findings.



RCA --- Recycled Coarse Aggregate, F --- Fibre, M --- Microsilica

Figure 111. Tensile splitting strength at 50% recycled coarse aggregate content

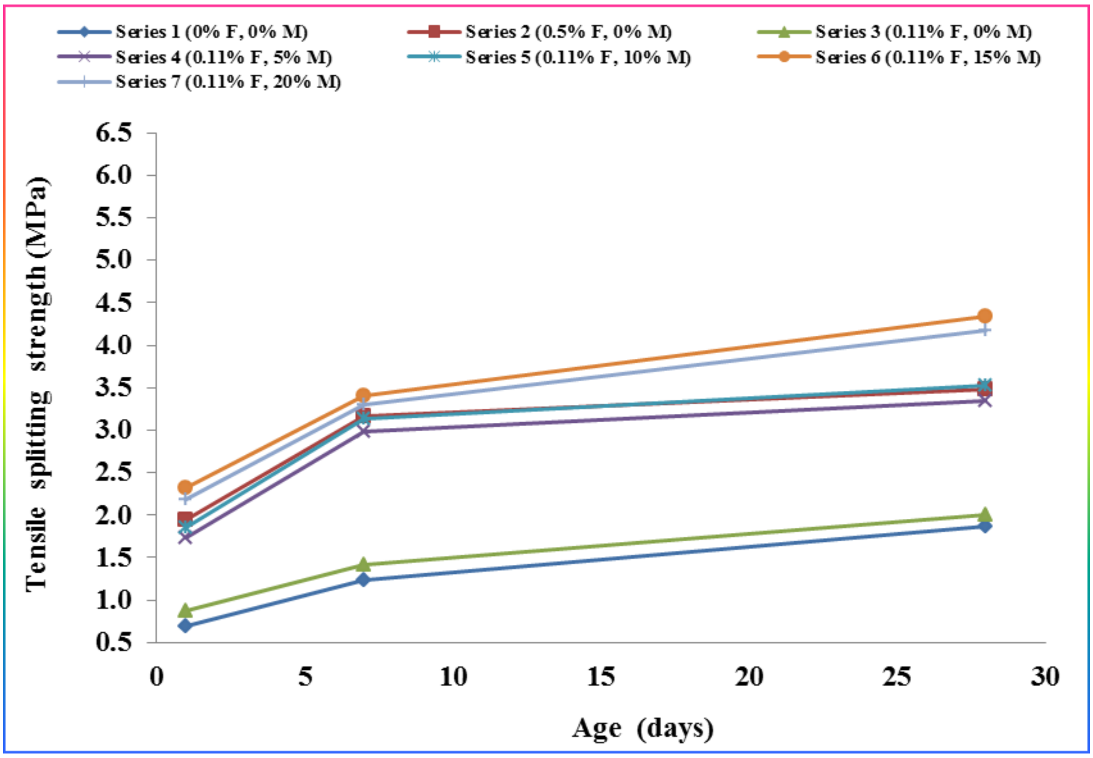
Results of 1, 7, and 28-day tensile splitting strength for concrete mix in Series 1, 4, 5, 6, and 7 respectively at 50% recycled coarse aggregate content is illustrated in figure 111. The tensile splitting strength gained by Series 6 concrete mix relative to the corresponding results from Series 1, 4, 5, and 7 concrete mixes were 85.4%, 35.3%, 18.6%, and 7.5% respectively. These results implies that the effect of increasing recycled coarse aggregate content in concrete mix is significant.



RCA --- Recycled Coarse Aggregate, F --- Fibre, M --- Microsilica

Figure 112. Tensile splitting strength a 75% recycled coarse aggregate content

Figure 112 illustrates the results of 1, 7, and 28-day tensile splitting strength for concrete mixes in Series 1, 4, 5, 6, and 7 respectively with 75% recycled coarse aggregate content. The relative reductions in 28-day tensile splitting strength for concrete mix in Series 1, 4, 5, and 7 respectively relative to Series 6 concrete mix were 55.3%, 22.2%, 19.1%, and 5.6% respectively. The results reflects the impact of increasing recycled coarse aggregate in the concrete mix and the influence of synthetic micro fibre addition.



RCA --- Recycled Coarse Aggregate, F --- Fibre, M --- Microsilica

Figure 113. Tensile splitting strength at 100% recycled coarse aggregate content

The tensile splitting strength results for concrete mix in Series 1, 4, 5, 6 and 7 at 1, 7, and 28-day curing age is illustrated in figure 113. The relative reduction in 28-day tensile splitting strength in Series 1, 4, 5, and 7 relative to the corresponding concrete mix in Series 6 were 56.9%, 22.8%, 8.89%, and 3.92% respectively. Tensile splitting strength of concrete mixes in Series 4, 5, and 7 respectively exceeded that of the corresponding control concrete Similar to Series 6 concrete mix irrespective of the percentage recycled coarse aggregate substitution. Figure 114 shows various patterns of failure identified from the concrete cylinder during tensile splitting strength test.

(a) Series 4 (0.11% F, 5% M)

(b) Series 5 (0.11% F, 10% M)

(c) Series 6 (0.11% F, 15% M)

(e) Series 7 (0.11% F, 10% M)

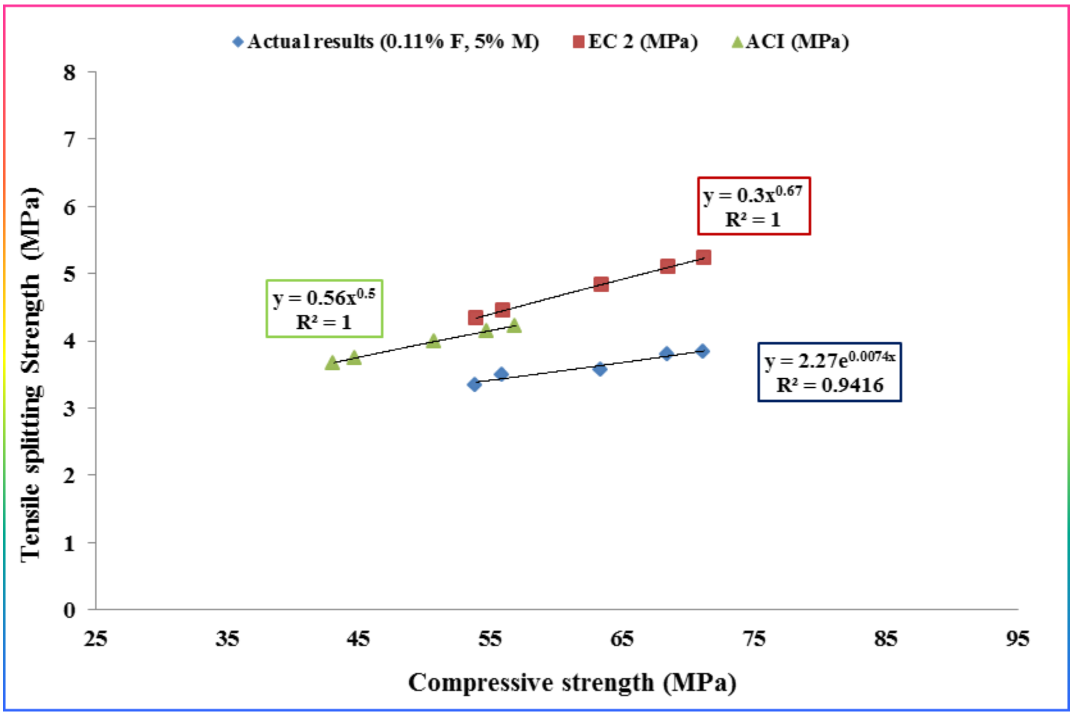
Figure 114. Failure patterns of cylinder specimens at 28-days compression test (0% RCA)

6.8 Correlations between Tensile splitting strength and compressive strength

Results of the comparison of compressive and tensile splitting strength obtained from the experiment and predictive equations given in EC-2 and ACI-318M are given in Table 48. EC-2 overestimated the tensile splitting strength of all the concrete mixes. However, ACI code overestimated concrete mixes with 0%, 25%, and 50% recycled aggregate while concrete mixes with 75% and 100% recycled aggregate were underestimated respectively. The relationship between the flexural and compressive strength is given by the exponential equation $\mathbf{f_{ctm,sp} = 1.43e^{0.02fck}}$ with a correlation coefficient $\mathbf{R^2 = 0.91}$.

Table 48: Experimental and predictive tensile splitting strength-Series 4 (0.11% F, 5% M)

RCA (%)	Experimental Compressive strength		Predicted Tensile splitting strength		Experimental Tensile splitting strength (MPa)
	fck, cube (MPa)	fck, cyl. (MPa)	EC 2 (MPa) $\{f_{ct,sp} = 0.30f_{ck}^{(2/3)}\}$	ACI (MPa) $\{f_r = 0.56\sqrt{fck'}\}$	
0	71.15	56.92	5.22	4.22	3.84
25	68.40	54.72	5.09	4.14	3.81
50	63.40	50.72	4.84	3.99	3.58
75	55.90	44.72	4.45	3.74	3.50
100	53.90	43.12	4.34	3.68	3.35



F --- Fibre, M --- Microsilica

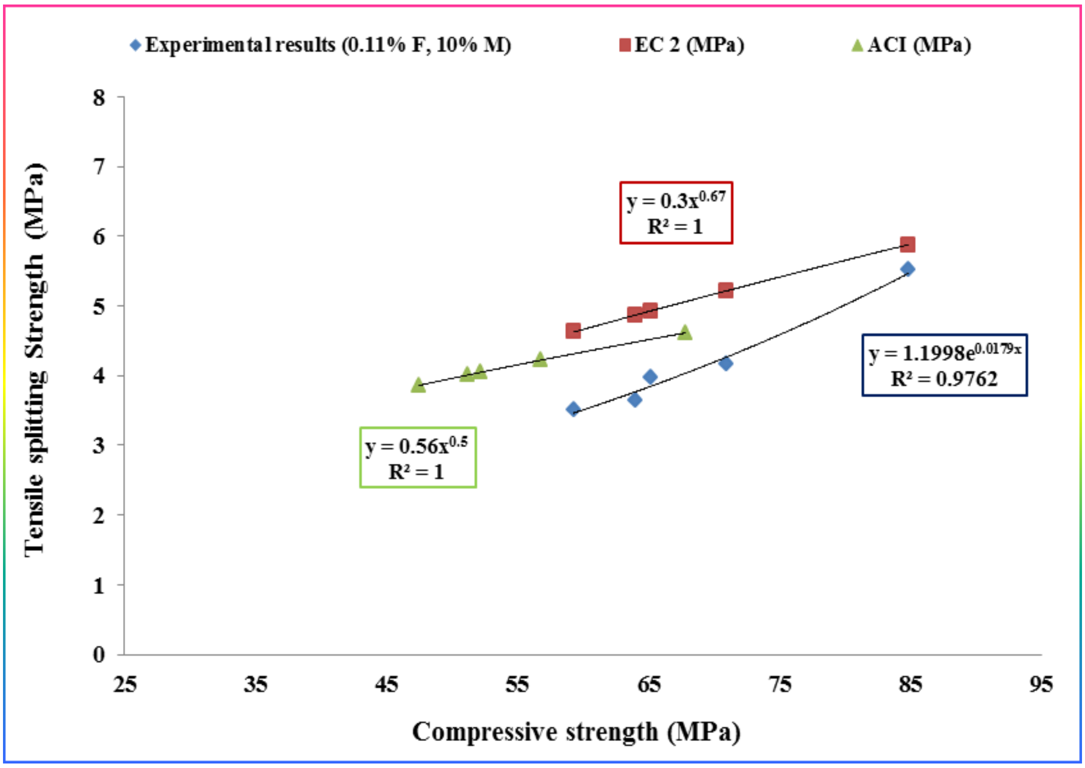
Figure 115. Relationship between Tensile splitting strength and compressive strength

Table 49: Experimental and predictive tensile splitting strength-Series 5(0.11% F, 10% M)

RCA (%)	**Experimental Compressive strength**		**Predicted Tensile splitting strength**		**Experimental Tensile splitting strength (MPa)**
	fck, cube (MPa)	**fck, cyl. (MPa)**	**EC 2 (MPa)** {$f_{ct,sp} = 0.30f_{ck}^{(2/3)}$}	**ACI (MPa)** {$f_r = 0.56\sqrt{fck'}$}	
0	84.84	67.87	5.88	4.61	5.52
25	71.00	56.80	5.22	4.22	4.17
50	65.20	52.16	4.93	4.04	3.97
75	63.98	51.18	4.87	4.01	3.64
100	59.30	47.44	4.62	3.86	3.52

Table 49 show the results of comparison between the experimental values and theoretical calculated values of flexural strength of concrete mixes in Series 5. It was identified that EC-2 overestimated flexural strength of all the concrete mixes in Series 5.

However, ACI also overestimate the flexural strength with the exception of the mix without recycled aggregate. The relationship obtained from Figure 116 indicate that an exponential trend exists between the flexural strength and compressive strength. This is given as $\mathbf{f_{ctm,sp} = 1.2e^{0.01fck}}$ with a correlation coefficient $\mathbf{R^2 = 0.98}$



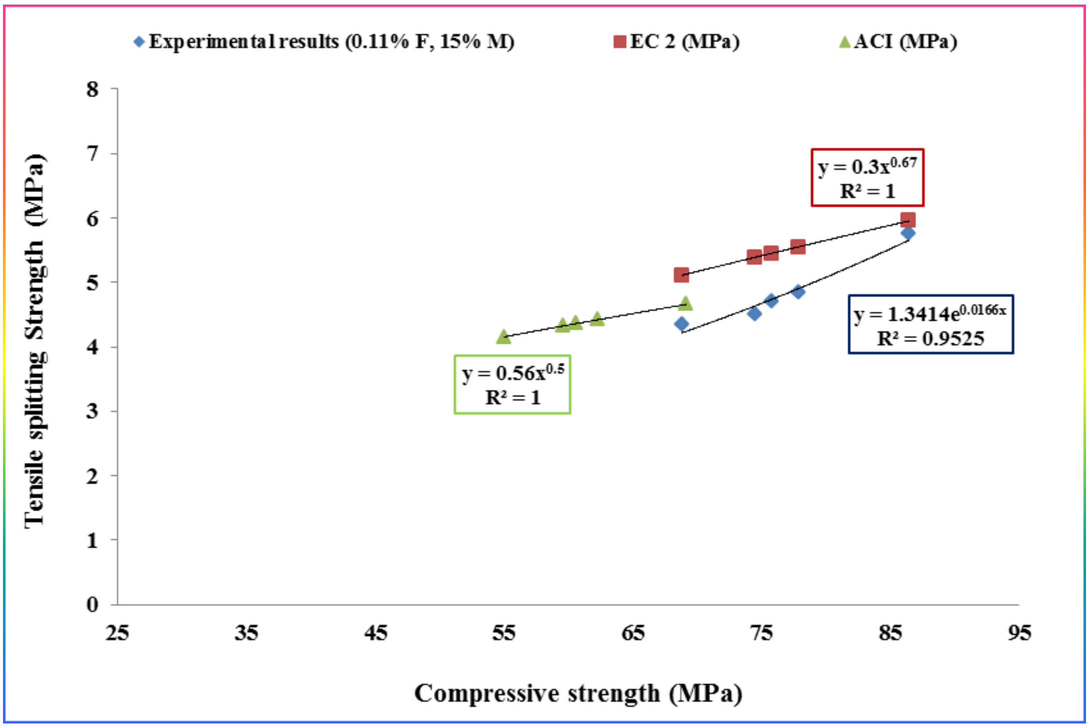
F --- Fibre, M --- Microsilica

Figure 116. Relationship between Tensile splitting strength and compressive strength

Table 50 and Figure 117 indicate that the predictive equation given in EC-2 overestimate the flexural strength of all the concrete mixes in Series 6, whereas ACI code underestimate the flexural strength. Similarly like the previous observation, the correlation between flexural strength and compressive strength remain exponential and it is given by the equation $\mathbf{f_{ctm,sp} = 1.34e^{0.02fck}}$ with a correlation coefficient $\mathbf{R^2 = 0.95}$

Table 50: Experimental and predictive tensile splitting strength-Series 6(0.11% F, 15% M)

RCA (%)	Experimental Compressive strength		Predicted Tensile splitting strength		Experimental Tensile splitting strength (MPa)
	fck, cube (MPa)	fck, cyl. (MPa)	EC 2 (MPa) $\{f_{ct,sp} = 0.30f_{ck}^{(2/3)}\}$	ACI (MPa) $\{f_r = 0.56\sqrt{fck'}\}$	
0	86.46	69.17	5.95	4.66	5.76
25	77.85	62.28	5.55	4.42	4.84
50	75.74	60.59	5.45	4.36	4.71
75	74.53	59.62	5.39	4.32	4.50
100	68.78	55.02	5.11	4.15	4.34



F --- Fibre, M --- Microsilica

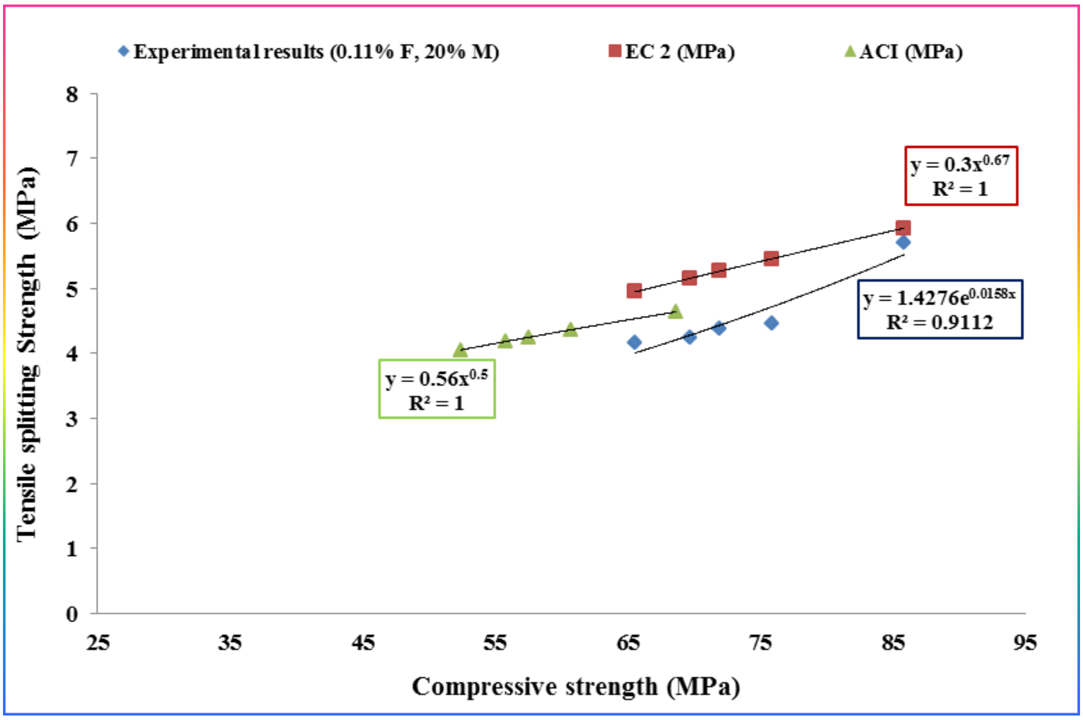
Figure 117. Relationship between Tensile splitting strength and compressive strength

The comparison of actual results of compressive and tensile splitting strength obtained from the experiment against the empirical values obtained from predictive equations given in EC-2 and ACI-318M are given in Table 51 and figure 118 respectively.

EC-2 slightly overestimated the tensile splitting strength of all the concrete mixes while ACI overestimated mixes with 0%, 25%, and 50% recycled coarse aggregate respectively but underestimate mixes with 75% and 100% recycled aggregate content. The correlation between tensile splitting strength and compressive strength is given by the equation $\mathbf{f_{ctm,sp} = 1.43e^{0.02fck}}$ with a correlation coefficient $\mathbf{R^2 = 0.91}$.

Table 51: Experimental and predictive tensile splitting strength-Series 7(0.11% F, 20% M)

RCA (%)	Experimental Compressive strength		Predicted Tensile splitting strength		Experimental Tensile splitting strength (MPa)
	fck, cube (MPa)	fck, cyl. (MPa)	EC 2 (MPa) $\{f_{ct,sp} = 0.30f_{ck}^{(2/3)}\}$	ACI (MPa) $\{f_r = 0.56\sqrt{fck'}\}$	
0	85.82	68.66	5.92	4.64	5.70
25	75.91	60.73	5.46	4.36	4.47
50	71.88	57.50	5.26	4.25	4.38
75	69.68	55.74	5.15	4.18	4.25
100	65.54	52.43	4.95	4.05	4.17



F --- Fibre, M --- Microsilica

Figure 118. Relationship between Tensile splitting strength and compressive strength

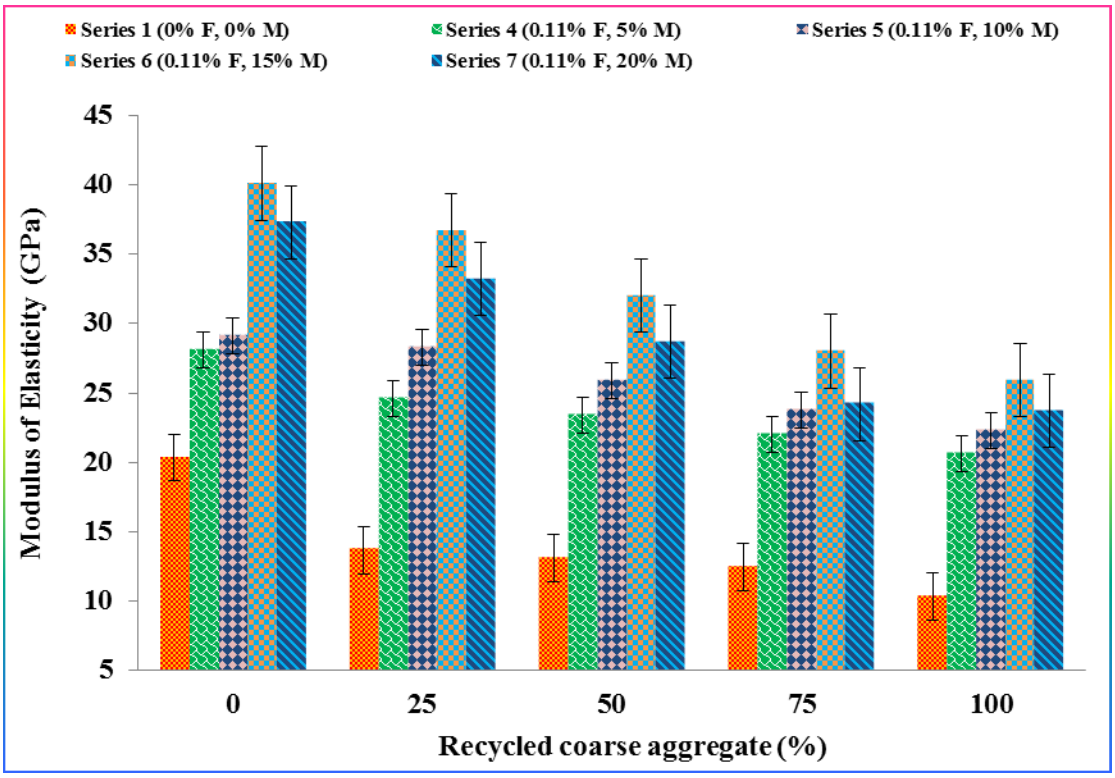
6.9 Static Modulus of Elasticity

Summary of the mean results of 28-day static modulus of elasticity recorded during the test for concrete mixes in Series 1, 4, 5, 6, and 7 respectively are given in table 34 and graphical representation of the variation of results illustrated in figure 119. The results shows reducing trend of elastic modulus with increasing percentage of recycled coarse aggregate in the concrete mix. For a given percentage of recycled coarse aggregate, results from Series 6 concrete mix incorporating 15% microsilica had the maximum static elastic modulus while concrete mixes in Series 1 without synthetic macro fibre and microsilica addition produced the least results.

Table 52: Summary of result of 28-day static modulus of elasticity

RCA (%)	Series 1 (0% F, 0% M)	Series 4 (0.11% F, 5% M)	Series 5 (0.11% F, 10% M)	Series 6 (0.11% F, 15% M)	Series 7 (0.11% F, 20% M)
0	20.35	28.10	29.10	40.10	37.30
25	13.66	24.60	28.30	36.70	33.20
50	13.10	23.40	25.90	32.00	28.70
75	12.43	22.00	23.80	28.00	24.20
100	10.33	20.60	22.30	25.90	23.70

RCA --- Recycled Coarse Aggregate, F --- Fibre, M --- Microsilica

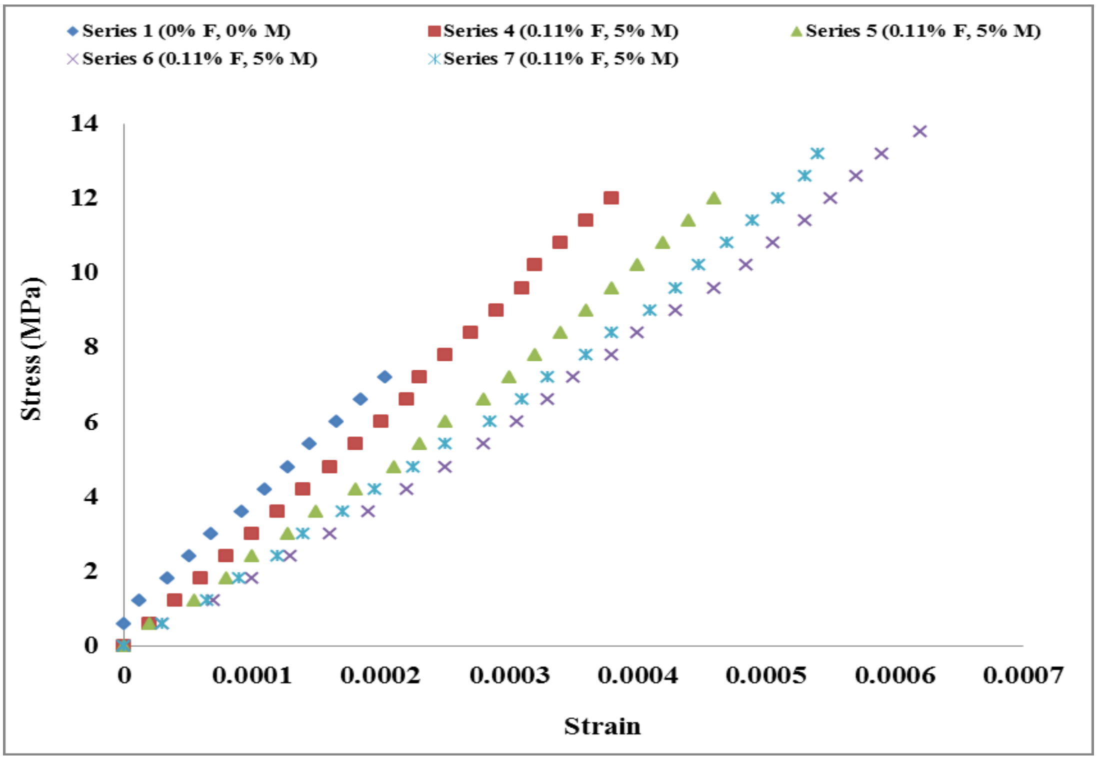


RCA --- Recycled Coarse Aggregate, F --- Fibre, M --- Microsilica

Figure 119. 28-day static modulus of elasticity

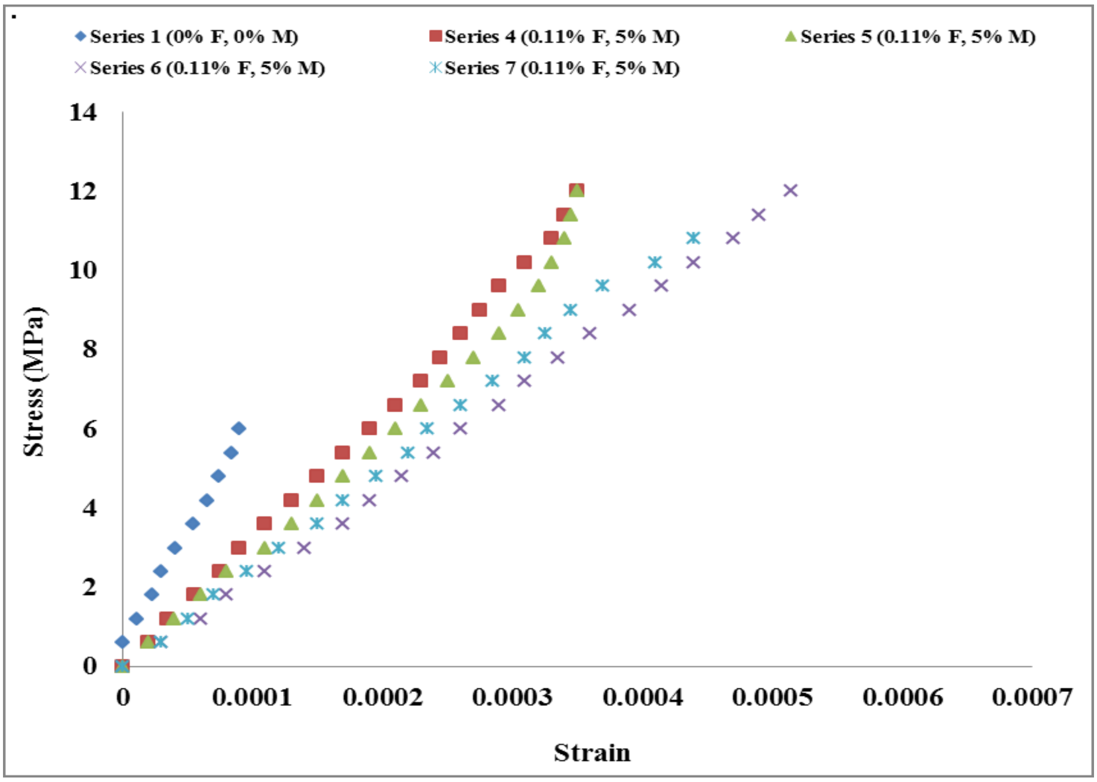
There were significant differences of about 49.9%, 53.7%, 60.1%, and 56.4% respectively in elastic moduli results between concrete mixes in Series 1 (control) at 100% recycled coarse aggregate content and corresponding mixes incorporating 5%, 10%, 15%, and 20% microsilica respectively. The maximum results occurred in concrete mixes in Series 6, which incorporates 15% microsilica addition. The general results indicate an increasing modulus of elasticity with increase in percentage content of microsilica up to 15% addition while further addition result in reduction. Therefore it could be concluded from the observation that the incorporation of microsilica and synthetic macro fibre have greater positive impact on modulus of elasticity. Burg and Ost (1992), recorded higher elastic moduli with concrete mix incorporating 15% microsilica addition compared with the reference concrete without any addition.

Similarly, a decreasing pattern of modulus of elasticity with increasing recycled coarse aggregate content occured and this was due to the lower modulus of elasticity associated with recycled coarse aggregate compared to the virgin coarse aggregate. Berndt (2009b), reported similar reduction as the recycled coarse aggregate content increased in the concrete mix. Xiao et al. (2005b) observed reduction of about 45% while Frondistou-Yannas (1977) suggested 40% reduction in elastic modulus at 100% recycled coarse aggregate content. The comparative stress-strain relationship for Series 1, 4, 5, 6 and 7 concrete mixes at various recycled coarse aggregate content are illustrated in Figures 120 - 124 respectively. It was generally observed across all the charts that the gradient of the stress-strain curve decreases with increasing recycled coarse aggregate content in the concrete mixes. The maximum gradient occurred at 0% recycled coarse aggregate content while the least gradient occurred at concrete mix with 100% recycled coarse aggregate content.



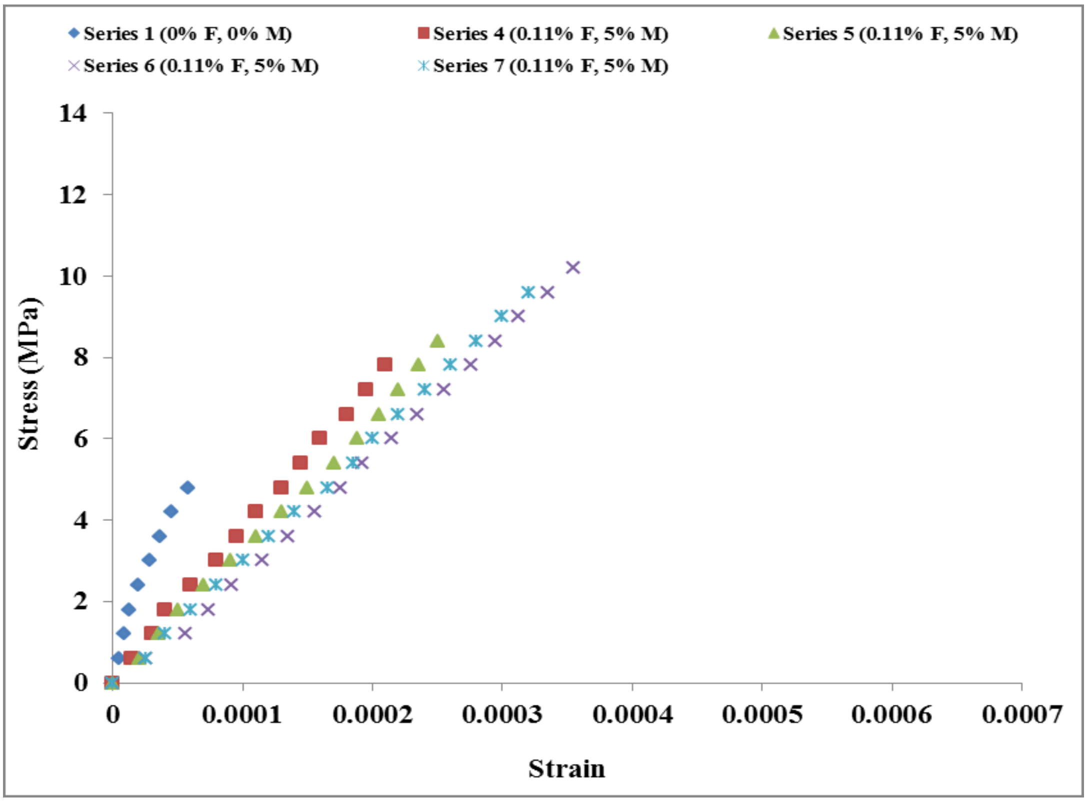
RCA --- Recycled Coarse Aggregate, F --- Fibre, M --- Microsilica

Figure 120. Stress-strain relationship for 0% recycled coarse aggregate content



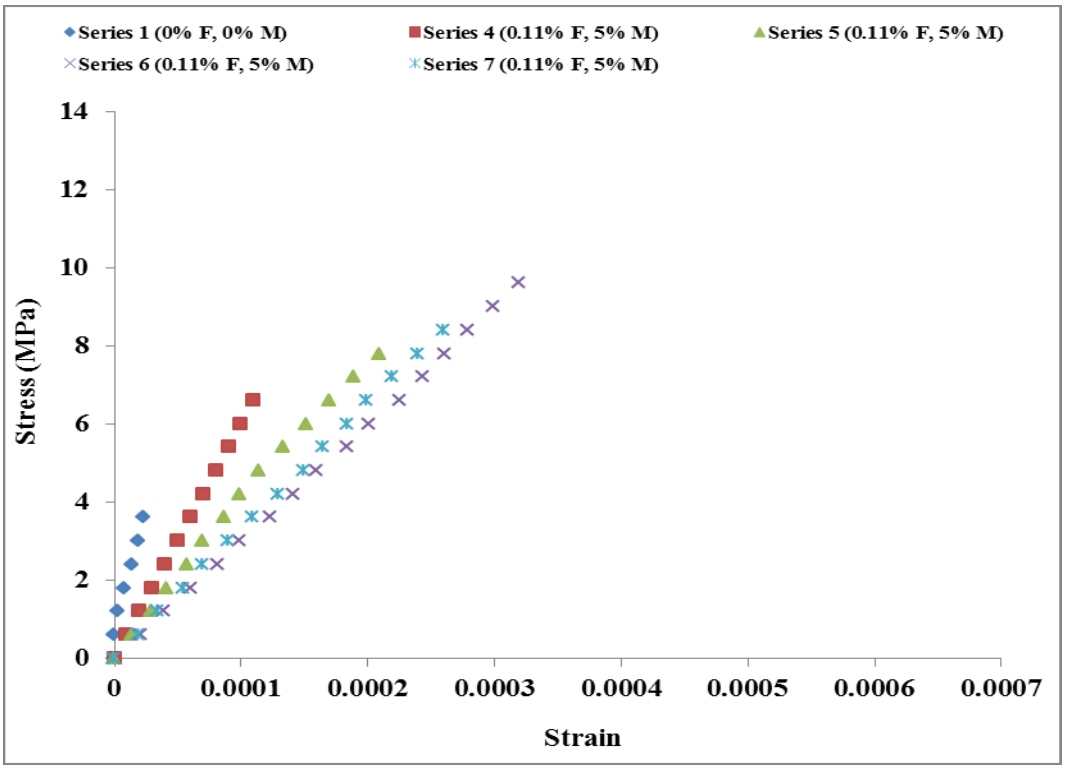
RCA --- Recycled Coarse Aggregate, F --- Fibre, M --- Microsilica

Figure 121. Stress-strain relationship for 25% recycled coarse aggregate content



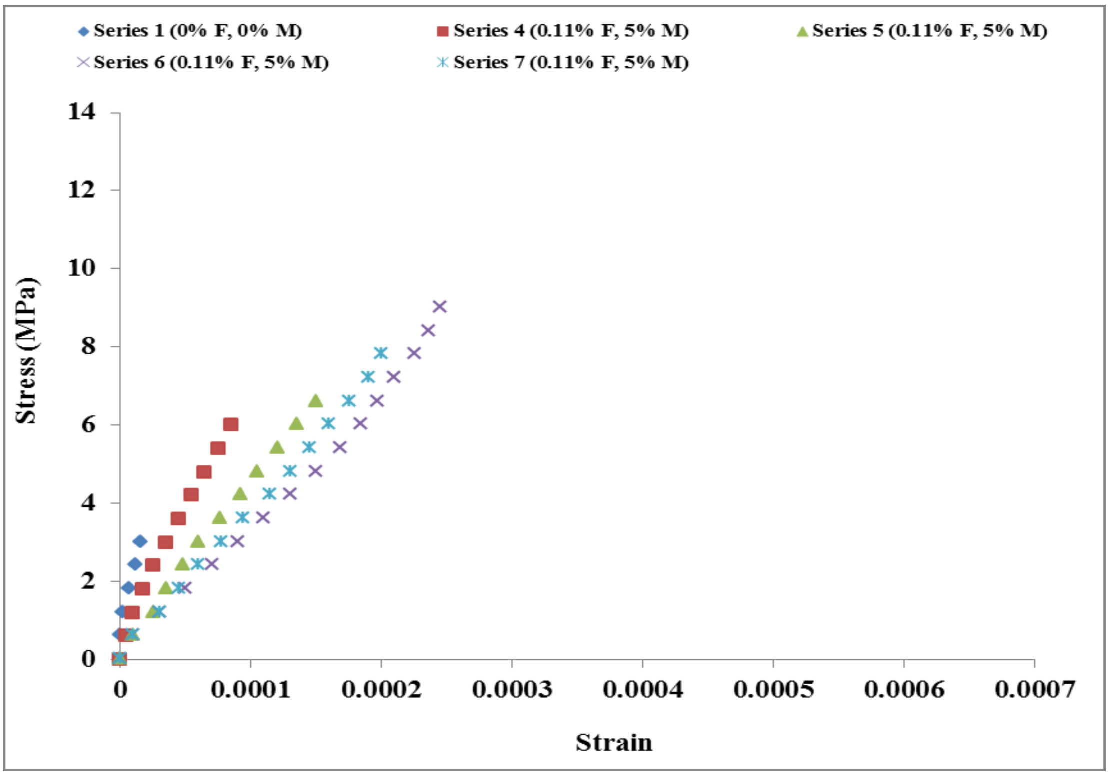
RCA --- Recycled Coarse Aggregate, F --- Fibre, M --- Microsilica

Figure 122. Stress-strain relationship for 50% recycled coarse aggregate content



RCA --- Recycled Coarse Aggregate, F --- Fibre, M --- Microsilica

Figure 123. Stress-strain relationship for 75% recycled coarse aggregate content



RCA --- Recycled Coarse Aggregate, F --- Fibre, M --- Microsilica

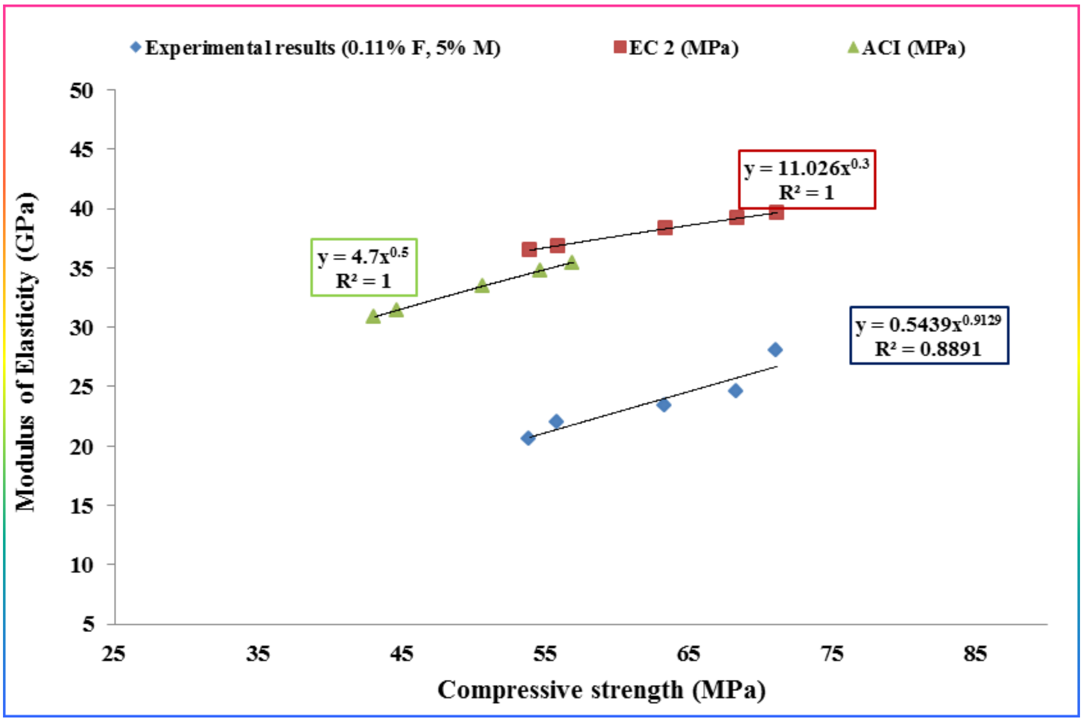
Figure 124. Stress-strain relationship for 100% recycled coarse aggregate content

6.10 Correlation between static elastic modulus and compressive strength

The relationship between static modulus of elasticity and compressive strength obtained experimentally and empirically from EC-2 and ACI-318M-14 are given in Tables 53 - 56 and illustrated in Figures 125 - 128 respectively. The results indicate that, the static modulus of elasticity increases with increasing compressive strength and vice-versa in Series 4, 5, 6, and 7 respectively. It was observed that the experimental results of modulus of elasticity are lower than the theoretical results. Table 53 -56 shows that both EC-2 and ACI overestimated the modulus of elasticity for the concrete mixes in Series 4, 5, 6, and 7 respectively with an exemption to the concrete mix in Series 6 at 0% recycled aggregate content.

Table 53: Experimental and predictive modulus of elasticity-Series 4 (0.11% F, 5% M)

RCA (%)	Experimental Compressive strength		Predicted elastic modulus		Experimental elastic modulus (GPa)
	fck, cube (MPa)	fck, cyl. (MPa)	EC 2 (GPa) $\{E_{cm} = 22\ [f_{cm}/10]^{0.3}\}$	ACI (GPa) $\{E_c = 4.7(f_c')^{0.5}\}$	
0	71.15	56.92	39.63	35.46	28.10
25	68.40	54.72	39.17	34.77	24.60
50	63.40	50.72	38.29	33.47	23.40
75	55.90	44.72	36.87	31.43	22.00
100	53.90	43.12	36.47	30.86	20.60

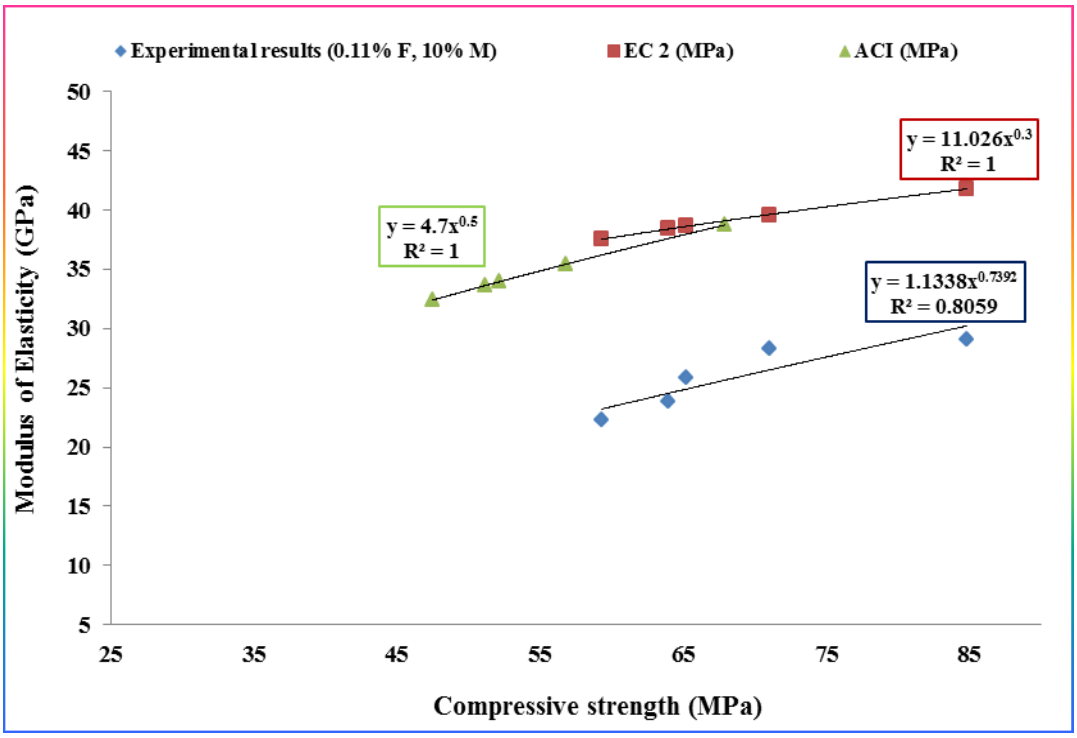


F --- Fibre, M --- Microsilica

Figure 125. Relationship between elastic modulus and compressive strength

Table 54: Experimental and predictive modulus of elasticity - Series 5 (0.11% F, 10% M)

RCA (%)	Experimental Compressive strength		Predicted elastic modulus		Experimental elastic modulus (GPa)
	fck, cube (MPa)	fck, cyl. (MPa)	EC 2 (GPa) $\{E_{cm}= 22\ [f_{cm}/10]^{0.3}\}$	ACI (GPa) $\{E_c = 4.7(f_c')^{0.5}\}$	
0	84.84	67.87	41.78	38.72	29.10
25	71.00	56.80	39.61	35.42	28.30
50	65.20	52.16	38.61	33.94	25.90
75	63.98	51.18	38.39	33.63	23.80
100	59.30	47.44	37.53	32.37	22.30

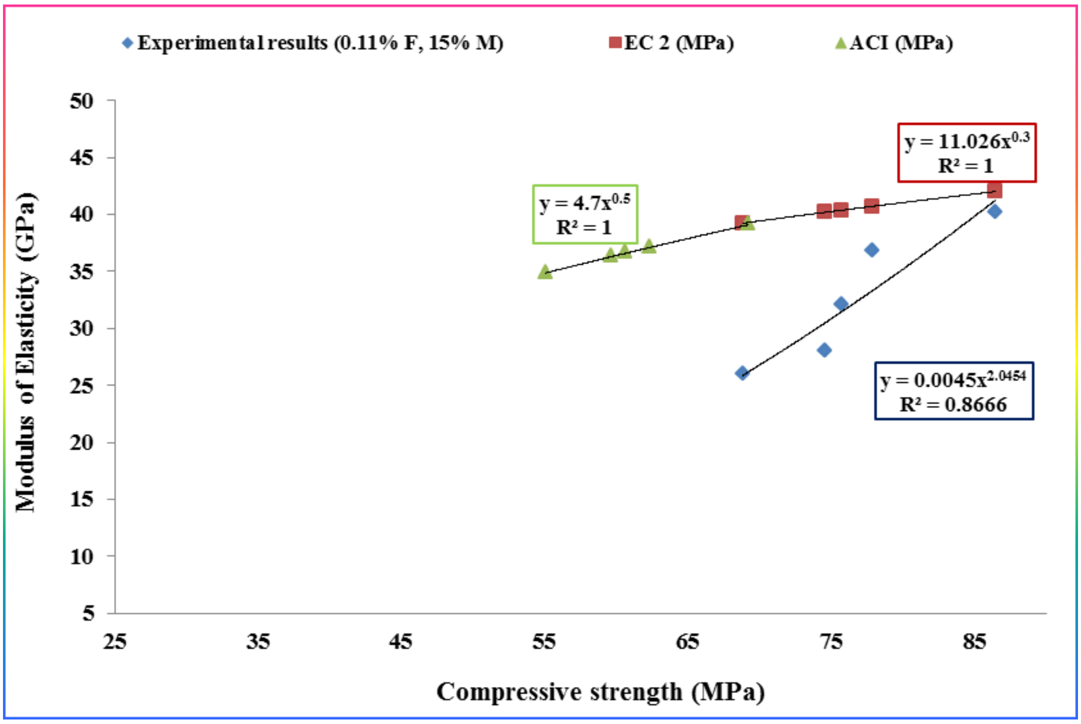


F --- Fibre, M --- Microsilica

Figure 126. Relationship between elastic modulus and compressive strength

Table 55: Experimental and predictive modulus of elasticity - Series 6 (0.11% F, 15% M)

RCA (%)	Experimental Compressive strength		Predicted elastic modulus		Experimental elastic modulus (GPa)
	fck, cube (MPa)	fck, cyl. (MPa)	EC 2 (GPa) {$E_{cm} = 22\,[f_{cm}/10]^{0.3}$}	ACI (GPa) { $E_c = 4.7(f_c')^{0.5}$}	
0	86.46	69.17	42.02	39.09	40.10
25	77.85	62.28	40.72	37.09	36.70
50	75.74	60.59	40.39	36.59	32.00
75	74.53	59.62	40.19	36.29	28.00
100	68.78	55.02	39.23	34.86	25.90

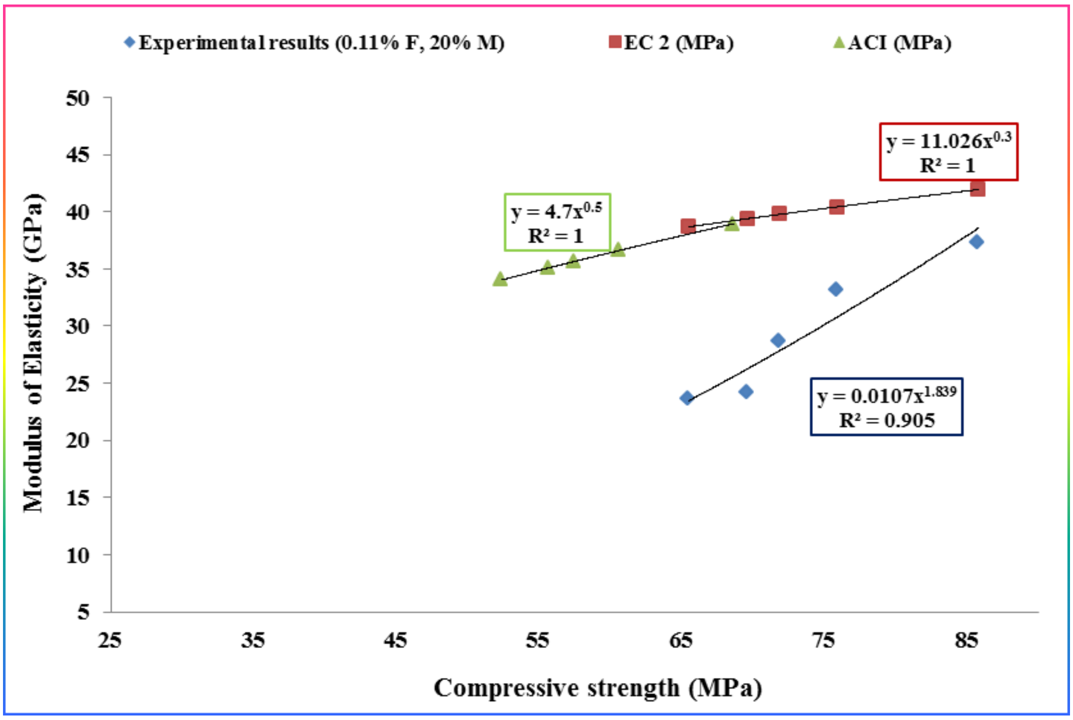


F --- Fibre, M --- Microsilica

Figure 127. Relationship between elastic modulus and compressive strength

Table 56: Experimental and predictive modulus of elasticity - Series 7 (0.11% F, 20% M)

RCA (%)	Experimental Compressive strength		Predicted elastic modulus		Experimental elastic modulus (GPa)
	fck, cube (MPa)	fck, cyl. (MPa)	EC 2 (GPa) $\{E_{cm} = 22\ [f_{cm}/10]^{0.3}\}$	ACI (GPa) $\{E_c = 4.7(f_c')^{0.5}\}$	
0	85.82	68.66	41.93	38.94	37.30
25	75.91	60.73	40.41	36.63	33.20
50	71.88	57.50	39.76	35.64	28.70
75	69.68	55.74	39.39	35.09	24.20
100	65.54	52.43	38.67	34.03	23.70



F --- Fibre, M --- Microsilica

Figure 128. Relationship between elastic modulus and compressive strength

The relationship between modulus of elasticity and compressive strength followed a power regression equation as shown in figures 125 – 128. Based on the regression analysis of the experimentally obtained test results, the correlations between the static modulus of elasticity and compressive strength of concrete investigated in Series 4, 5, 6, and 7 respectively are given below with their coefficient of corelation:

$E_{cm} = 0.54fck^{0.91}$ ($R^2 = 0.89$) -----------------Series 4 (0.11% F, 5% M)

$E_{cm} = 1.13fck^{0.74}$ ($R^2 = 0.81$) ---------------- Series 5 (0.11% F, 10% M)

$E_{cm} = 0.005fck^{2.04}$ ($R^2 = 0.87$) ---------------Series 6 (0.11% F, 15% M)

$E_{cm} = 0.01fck^{1.84}$ ($R^2 = 0.91$) ---------------Series 6 (0.11% F, 15% M)

6.11 Water Permeability Test (Autoclam)

Figures 129 -132 illustrates the relationship between the average cumulative volume of water inflow into the concrete cubes and the square root of time. The graphs indicate that a linear relationship exist as shown in line equation displayed in tables 35-39 obtained from the regression line from which the gradient of the trendlines representing the sorptivity indices shown in the tables were derived.

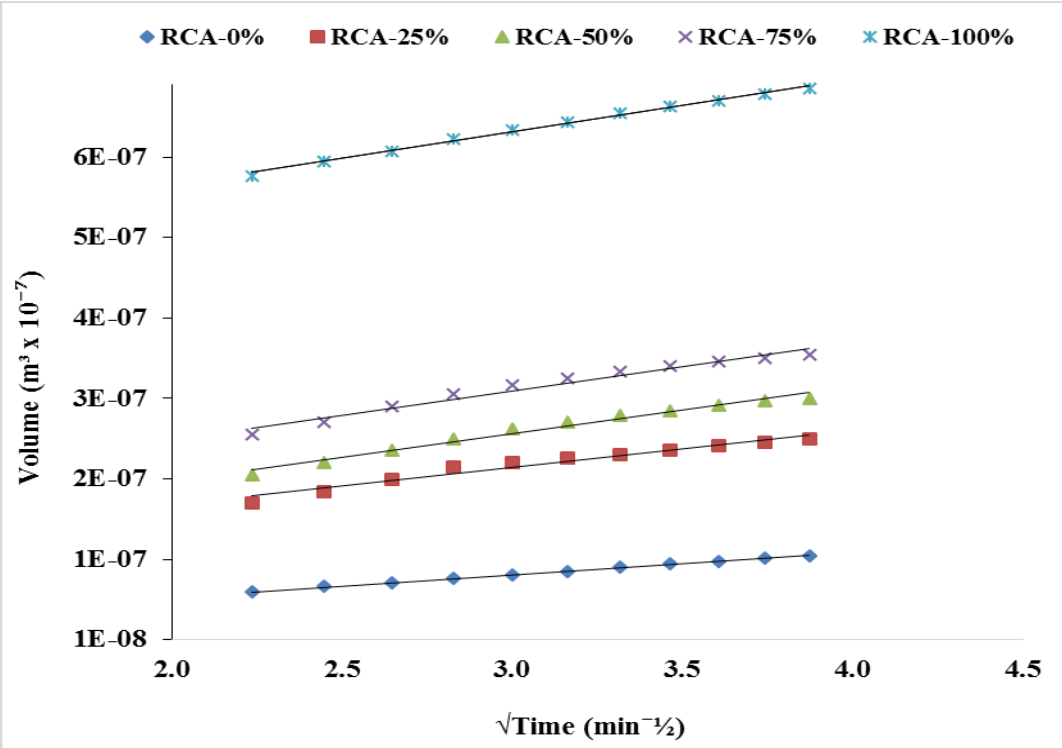
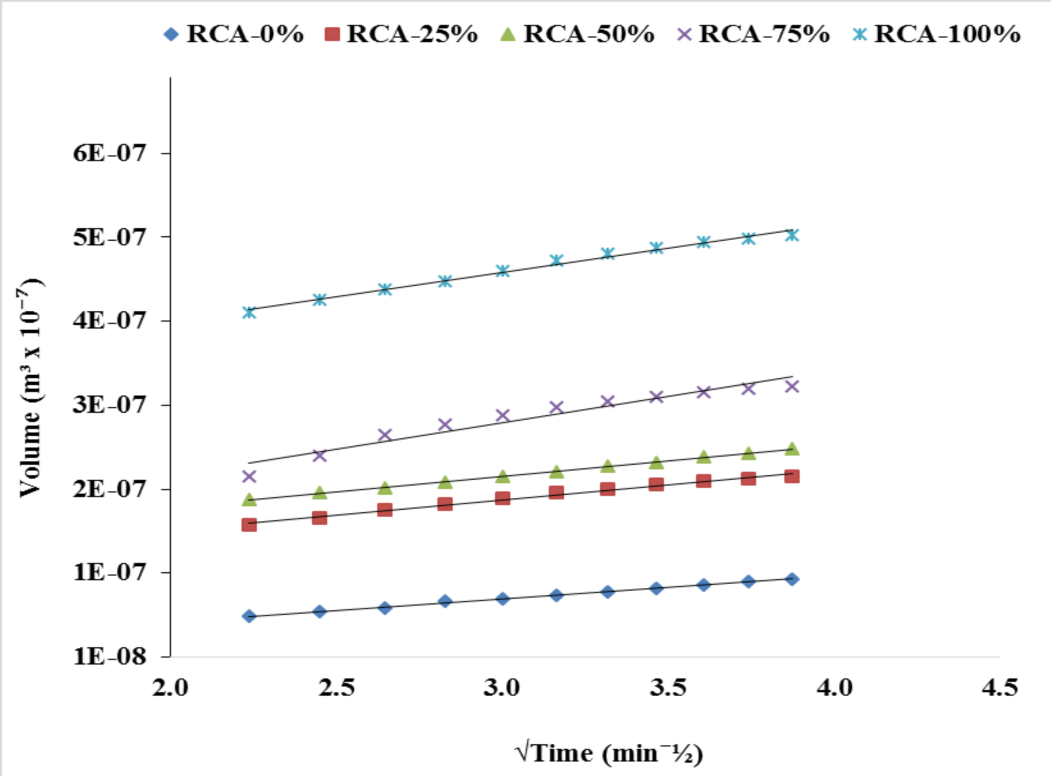


Figure 129. Graph of cumulative water volume & square root of time (Series 4 - 0.11% F, 5% M)

Table 57: Parameters from cumulative water volume-square root of time graph (Series 4- 0.11% F, 5% M)

Mix ID	Line Equation	Sorptivity Index (x 10^{-7})	R^2
RCA-0%	3E-08x + 7E-09	0.3	0.9984
RCA-25%	5E-08x + 8E-08	0.5	0.9587
RCA-50%	6E-08x + 9E-08	0.6	0.9799
RCA-75%	6E-08x + 1E-07	0.6	0.97
RCA-100%	7E-08x + 4E-07	0.7	0.9959

RCA --- Recycled Coarse Aggregate, F --- Fibre, M --- Microsilica



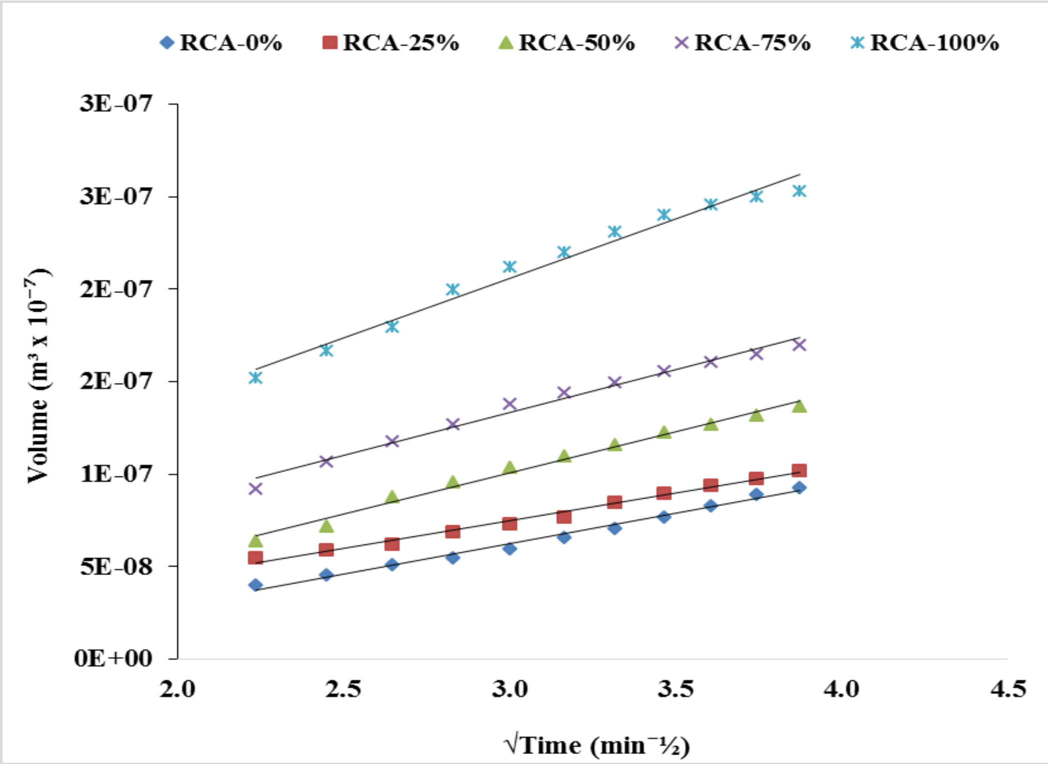
RCA --- Recycled Coarse Aggregate, F --- Fibre, M --- Microsilica

Figure 130. Graph of cumulative water volume & square root of time (Series 5 - 0.11% F, 10% M)

Table 58: Parameters from cumulative water volume-square root of time graph (Series 5 - 0.11% F, 10% M)

Mix ID	Line Equation	Sorptivity Index (x 10^{-7})	R^2
RCA-0%	3E-08x + 3E-09	0.3	0.997
RCA-25%	4E-08x + 9E-08	0.4	0.9888
RCA-50%	4E-08x + 1E-07	0.4	0.9987
RCA-75%	6E-08x + 1E-07	0.6	0.9376
RCA-100%	6E-08x + 3E-07	0.6	0.9885

RCA --- Recycled Coarse Aggregate, F --- Fibre, M --- Microsilica



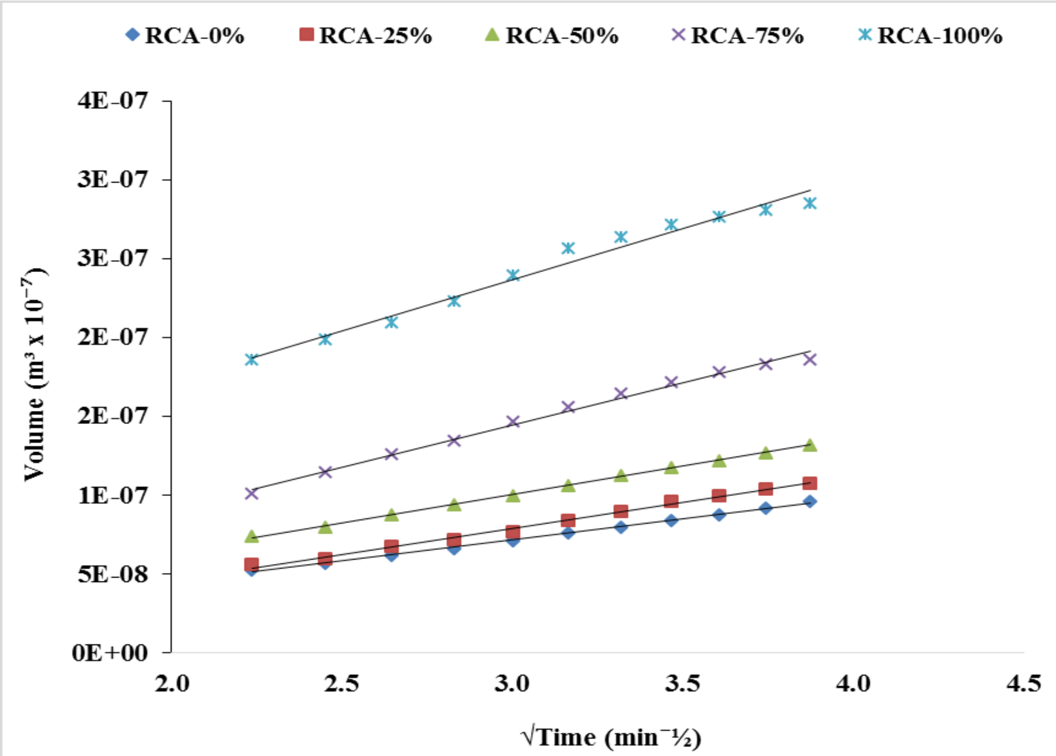
RCA --- Recycled Coarse Aggregate, F --- Fibre, M --- Microsilica

Figure 131. Graph of cumulative water volume & square root of time (Series 6 - 0.11% F, 15% M)

Table 59: Parameters from cumulative water volume-square root of time graph (Series 6 - 0.11% F, 15% M)

Mix ID	Line Equation	Sorptivity Index (x 10^{-7})	R^2
RCA-0%	3E-08x + 4E-08	0.3	0.989
RCA-25%	3E-08x + 2E-08	0.3	0.9886
RCA-50%	4E-08x + 3E-08	0.4	0.9877
RCA-75%	5E-08x + 6E-09	0.5	0.9846
RCA-100%	6E-08x + 1E-08	0.6	0.9789

RCA --- Recycled Coarse Aggregate, F --- Fibre, M --- Microsilica



RCA --- Recycled Coarse Aggregate, F --- Fibre, M --- Microsilica

Figure 132. Graph of cumulative water volume & square root of time (Series 7 - 0.11% F, 20% M)

Table 60: Parameters from cumulative water volume-square root of time graph (Series 7 - 0.11% F, 20% M)

Mix ID	Line Equation	Sorptivity Index (x 10^{-7})	R^2
RCA-0%	3E-08x + 8E-09	0.3	0.9972
RCA-25%	3E-08x + 2E-08	0.3	0.9951
RCA-50%	4E-08x + 7E-09	0.4	0.999
RCA-75%	5E-08x + 2E-08	0.5	0.9916
RCA-100%	6E-08x + 4E-08	0.6	0.9769

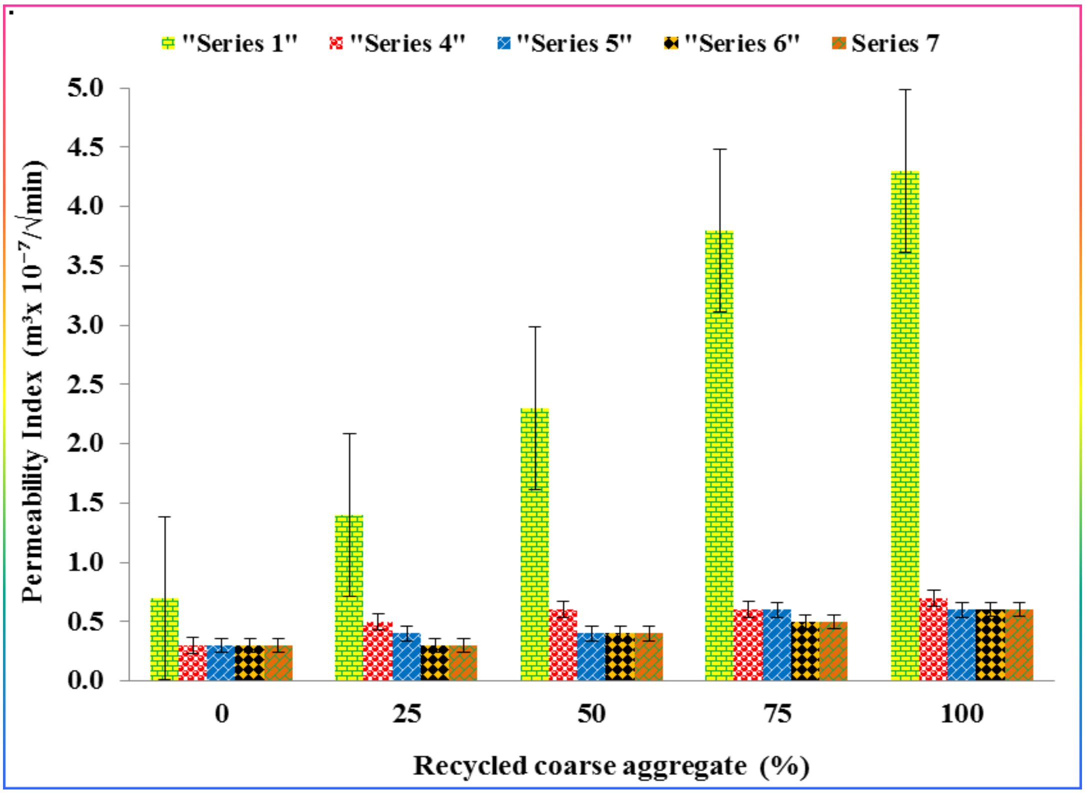
RCA --- Recycled Coarse Aggregate, F --- Fibre, M --- Microsilica

Table 61 displayed the summary of sorptivity indices from the results of 28-day water permeability test conducted on Series 1, 4, 5, 6 and 7 concrete mixes respectively, while the graphical illustration showing the increase in permeability with increasing recycled coarse aggregate content in each of the mix is given in Figure 133. For a given recycled coarse aggregate content, the control mix in Series 1 had the maximum permeability indices compared to Series 4-7 which incorporates micro silica and low volume of synthetic macro fibre.

Table 61: Summary of sorptivity indices of 28-day permeability test on concrete cubes

RCA (%)	**Series 1** (0% F, 0% M) (x 10⁻7)	**Series 4** (0.11% F, 5% M) (x 10⁻7)	**Series 5** (0.11% F, 10% M) (x 10⁻7)	**Series 6** (0.11% F, 15% M) (x 10⁻7)	**Series 7** (0.11% F, 20% M) (x 10⁻7)
0	0.7	0.3	0.3	0.3	0.3
25	1.4	0.5	0.4	0.3	0.3
50	2.3	0.6	0.4	0.4	0.4
75	3.8	0.6	0.6	0.5	0.5
100	4.3	0.7	0.6	0.6	0.6

RCA --- Recycled Coarse Aggregate, F --- Fibre, M --- Microsilica



RCA --- Recycled Coarse Aggregate, F --- Fibre, M --- Microsilica

Figure 133. 28-day water permeability (Autoclam) results

Table 62:. Protective quality of concrete

Protective quality of concrete based on Clam permeation indices after (Concrete-Society, 2008)				
Permeation Property	**Protective Property**			
	Very good	Good	Poor	Very poor
Clam Water Permeability (m³×E-7/√min)	≤ 3.70	> 3.70 ≤ 9.40	> 9.40 ≤ 13.8	> 13.8

Generally, the results indicate that sorptivity indices reduces with increasing content of microsilica until the optimum addition was reached while increase in recycled coarse aggregate content increases permeability and vice-versa. Concrete mixes in series 4-7, which incorporates microsilica respectively, produced the least permeability indices compared to the reference mix with the most improved mix being Series 6 and 7 respectively. According to Table 62, Concrete in Series 4–7 fell under the very good protective quality of concrete from 0-100% recycled coarse aggregate content while the control concrete in Series 1 fell under very good to good.

Overall, the concrete produced from this experimental work are adjudged durable concrete and the improved durability performance of concrete mixes incorporating microsilica was due to the microfiller impact that alters the microstructure of the concrete. Song et al. (2010), mentioned that the addition of microsilica reduced permeability due to its densifying effect on microstructure which subsequently lead to reduction in porosity and emergence of denser concrete. Mangat and Azari (1984) linked the reduction in permeability due to incorporation of fibre to the tendency of fibres to reduce cracks emanating from shrinkage. It was further suggested that discontinuity of pores and inter-connectivity of porous links could be responsible for for this effect. The substitution by 75% and 100% recycled coarse aggregate in Series 1 increased the permeability to about 3.8 and 4.3 $x10^{-7} m^3/\sqrt{min}$ respectively, although the effect was insignificant to the entire durability property. The higher permeability observed was due to the adhered mortar on recycled coarse aggregate. Yang et al. (2011) also reported that concrete mix with 100% recycled coarse aggregate was more permeable (about 21%) than the control mix with 0% recycled coarse aggregate. This was attributed this to the presence of more proportion of attached mortar on recycled coarse aggregate. Limbachiya et al. (2000) and Pandit and Parameswari (2014) also agreed that more recycled coarse aggregate content in concrete mix increased the permeability.

6.12 Summary of findings

The main conclusions from this experimental work are as follows:

1) Incorporation of 5, 10, 15, and 20% mineral admixture (microsilica) greatly improved the compressive strength, tensile splitting strength, flexural strength, static modulus of elasticity and reduced water permeability respectively;
2) The density of concrete in fresh and hardened state decreases with increasing recycled aggregate content in the concrete mix.
3) Fresh and hardened state densities of concrete with high dosage of fibre is lower than the density of concrete without fibre.
4) The fresh and hardened state densities of concrete incorporating microsilica produced higher results than others due to microsilica's ability to effect densification in concrete.
5) The engineering properties of concrete mix incorporating 15% microsilica in Series 6 were greatly improved with reference to the strength gained and durability compared to others mixes;
6) The modulus of elasticity of concrete mix with 15% microsilica exceeds the theoretical value of 35 GPa given in Table 3.1 of BS-EN 1992-1-1:2004 by 14.6% and 4.9% respectively at 0% and 25% recycled coarse aggregate content while the mixes incorporating 50%, 75%, and 100% recycled coarse aggregate content fell below the theoretical value by 8.6%, 20%, and 26% respectively.

7 FATIGUE ASSESSMENT OF RECYCLED AGGREGATE CONCRETE INCORPRATING MICRO SILICA AND FIBRE

7.1 Introduction

The results of the investigation on flexural fatigue performance of concrete mixes under cyclic (repetitive) loading using three-point bending tests is discussed in this chapter. The concrete mixes in chapter 6 which incorporate microsilica at 15% by weight of cement, recycled aggregate, and 0.11% synthetic macro fibre are the focus of the investigation. Many researchers have studied and reported various findings on fatigue behaviour of conventional plain concrete and steel fibre reinforced concrete as well as concrete incorporating microsilica. However, to the best knowledge of the researcher, no one has carried out or reported any investigation involving recycled coarse aggregate concrete incorporated with microsilica and synthtetic macro fibre. The aim of this study therefore, was to assess the impact of recycled coarse aggregate, microsilica and synthetic macro fibre on concrete subjected to test under static and cyclic (fatigue) loading respectively. Comparison will be made with the results obtained from normal (plain) concrete.

Detailed information will be provided with vital findings such as the fatigue life. A total of seventy five (75) prismatic concrete specimens were investigated under both static and cyclic loading respectively. The concrete mix consist of five batches and each batch is made up of fifteen (15) standard concrete prisms of dimensions 100 x 100 x 500 mm. Static loading was carried out in order to determine the maximum flexural strength of the concrete prisms using three-point bending tests which was adopted for the cyclic loading. The reason was to assess the differences between the flexural strength results obtained from three-point bending test and four-point bending test reported in chapter 6. The tests were conducted at various stress levels of 65%, 75%, 85% and 95% of static capacity respectively at a loading frequency of 3Hz and high-cycle fatigue loading of 100,000 cycles. The flexural fatigue loading was discontinued once the concrete prism specimen failed or when the target cycles were reached depending on whichever occurred first. The fatigue analysis followed a sinusoidal wave pattern and the result of the relationship between various stress levels (S) and corresponding number of cycles (N) is represented by a widely accepted empirically derived S-N curve diagram known as Wohler curves. This was derived from the experimental data during the analysis.

7.2 Flexural fatigue life

Table 63 displays the results of four-point and three-point bending test from the Avery-Denison machine used for flexural strength test, and servo-hydraulic digital controlled actuator machine used for fatigue loading respectively.

Table 63: Comparison of 4-point bending and 3-point bending flexural strength test

4-point bending test (MPa)			**3-point bending test (MPa)**	
RCA (%)	Concrete without microsilica	Concrete with 15% microsilica	Concrete without microsilica	Concrete with 15% microsilica
0	8.40	9.17	4.20	4.94
25	6.00	7.50	3.30	4.50
50	4.74	6.40	2.75	4.17
75	4.08	5.70	2.40	3.73
100	3.82	5.40	2.27	3.44

RCA ---- Recycled Coarse Aggregate

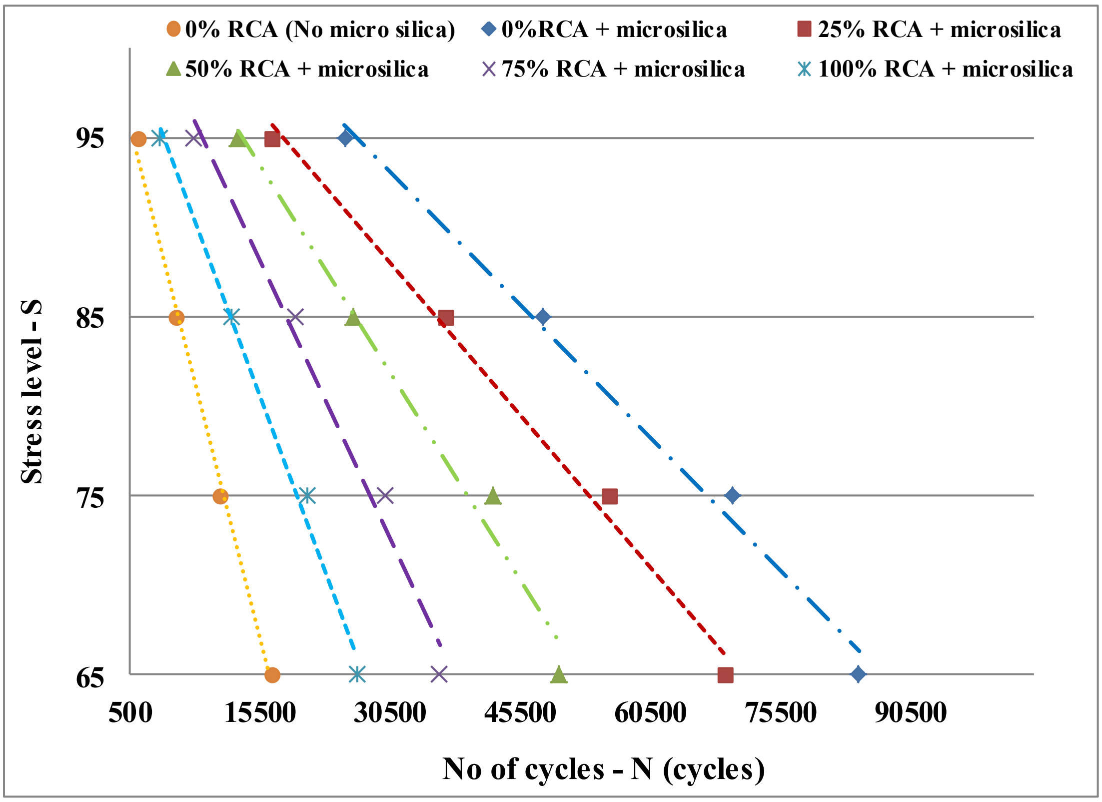
The results of fatigue analysis on high performance recycled aggregate concrete incorporating synthetic macro fibre are presented in table 42.

Table 64: Result of flexural fatigue assessment

Stress Level (S)	Fatigue Life N (Cycles)					
	Series 1 100%NA-0%RCA	Series 6 (with 15% microsilica)				
		100%NA-0%RCA	75%NA-25%RCA	50%NA-50%RCA	25%NA-75%RCA	0%NA-100%RCA
95	1400	25400	17000	13000	8000	4000
85	5800	48200	37000	26400	19600	12400
75	11000	70200	55800	42600	30000	21000
65	17000	84800	69200	50200	36400	26800

NA---Natural coarse aggregate, RCA----Recycled coarse aggregate

The relationship between the stress levels (S) and number of cycle (N) widely referred to as Wohler curves or S-N curves is represented by the linear regression line with constant slope in Figure 134. The response of the concrete prism specimens to cyclic loading was represented by the S-N curves, which shows graphical relationship between different stress levels and the number of cycles sustained by the concrete prism before failure occurred for each applied stress levels. The relationship observed between the two parameters is linear and of the form ax + b. This was obtained through the equation of linear regression and these parameters are given in Table 65.



RCA --- Recycled Coarse Aggregate

Figure 134. 28-day S-N curves of concrete prisms with 15% micro silica content (Series 6)

The coefficient of regression R^2 is significantly close to unity in all the trendlines for each of the concrete mix as indicated in Table 65. Seitl et al. (2010) also reported higher coefficient of regression for concrete mix incorporated with microsilica compared to concrete mix without microsilica addition. The test results indicate that all the concrete mixes followed a similar trend as the fatigue life under the same stress level decreases with increasing recycled aggregate content, while the fatigue life increases as the stress level decreases and vice-versa. Concrete incorporated with microsilica and synthetic macro fibre sustained more cyclic loading than the conventional plain concrete samples in Series 1 without microsilica addition. This implies that high performance concrete incorporating recycled coarse aggregate and synthetic macro fibre are less brittle than conventional plain concrete under repetitive loading.

Table 65: Parameters obtained from S-N curve for Series 6 concrete mix.

Parameters	Type of concrete mix					
	Series 1 (without micro-silica)	Series 6 (with 15% microsilica)				
	0% RCA	0% RCA	25% RCA	50% RCA	75% RCA	100% RCA
a	-0.0019	-0.0005	-0.0006	-0.0008	-0.001	-0.0013
b	96.84	108.28	105.32	105.4	104.2	100.69
R^2	0.9953	0.9906	0.9924	0.9821	0.9846	0.9928

RCA --- Recycled Coarse Aggregate

Where '**a**' represent slope, '**b**' is the intercept from the chart, '**R^2**' stands for the coefficient of correlation and **RCA** denotes Recycled coarse aggregate.

The test results indicates that all the concrete mix followed similar trend as the fatigue life under the same stress level decreases with increasing recycled aggregate content, while the fatigue life increases as the stress level decreases and vice-versa.

The incorporation of synthetic macro fibre impacted on the behaviour of the concrete due to its ability to bridge microcracks and reduce crack growth which subsequently contribute to the improvement of the performance of the concrete under cyclic loading and thus further prolong the fatigue life of the concrete prism samples. It was intended to carry out comparisons of the results obtained from this research work with other studies where a combination of synthetic macro fibre, microsilica, and recycled coarse aggregate were used in concrete mix. However, due to little or no available research literature on the performance of these materials incorporated together in concrete mix under flexural fatigue loading, their separate influence on fatigue behaviour of concrete would be examined against their respective contributions rather than collective contributions.

Most research findings dealt with these materials as a separate entity in concrete. Thomas et al. (2014a), reported reduction in fatigue life of concrete incorporated with recycled aggregate compared to normal aggregate concrete. This was linked to the low strength of recycled coarse aggregate leading to loss of stiffness. However, recycled aggregate content at about 20% substitution for natural coarse aggregate was not affected. The S-N curve under flexural cyclic loading indicate a linear relationship from the trendlines as illustrated in Figure 134. However, the significant influence of microsilica and synthetic macro fibre were observed in concrete mixes incorporated with microsilica and synthetic micro fibre respectively, compared with the plain concrete without microsilica and fibre addition in Series 1.

7.3 Summary of findings

The main conclusions from this experimental work are as follows:

1) A linear relationship exist between the stress levels and fatigue life of recycled aggregate concrete incorporating micro silica and synthetic macro fibre.
2) Fatigue life decreases with increasing recycled coarse aggregate content in the concrete mix.

3) The stress level reduces with increase in recycled coarse aggregate content in the concrete mix and vice-versa.
4) Concrete incorporated with microsilica and synthetic macro fibre sustained more cyclic loading than normal concrete without micro silica and synthetic macro fibre addition.

8 CONCLUSIONS AND RECOMMENDATIONS

8.1 Conclusions

The conclusion of all the major findings from phases one, two and three of the research work is presented under this chapter for clarity of purpose. The researcher, in line with the aim and objectives of the study have identified four key areas involving major experimental work. These areas are;

1) Assessment of the impact of incorporating synthetic macro fibre and microsilica on the physical and mechanical properties of recycled coarse aggregate concrete;
2) Assessment of the durability of the concrete produced from these materials;
3) Determination of the optimaum ratio of microsilica to enhance the performance of the concrete; and
4) Evaluation of the response and performance of the fibre reinforced concrete to fatigue loading.

The conclusions from this experimental work are;

1) The water absorption of recycled coarse aggregate is about five times the absorption for natural coarse aggregate
2) Higher recycled coarse aggregate fraction in concrete mix results in a significant reduction in physical and mechanical properties of concrete.
3) The incorporation of synthetic macro fibre to concrete mix, had little or no significant effect on the compressive strength of concrete.
4) The incorporation of higher fraction of microsilica, significantly improved the engineering properties of recycled aggregate concrete up to 15% addition, beyond which the engineering properties decline.

5) Addition of synthetic macro fibre and microsilica increased the fatigue life of recycled aggregate concrete ans also reduced the permeability.
6) The theoretical modulus of elasticity of concrete predicted by EC-2 and ACI overestimate the experimental value of modulus of elasticity.
7) The impact of incorporating fibre in the concrete mixes was significant on flexural strength, tensile splitting strength and static modulus of elasticity respectively.
8) The outcome of this research suggests a strong potential to increase the current recommended fraction of recycled coarse aggregate in concrete from 30% to 50% in terms of strength.
9) Application of research results will boost the confidence in the use of recycled aggregate, help in conservation of the natural resources (quarry) and increase the sustainability credentials of the construction sector.

8.2 Recommendations

Although the study have shown the limits to which microsilica addition is optimal in concrete, the appreciable benefits and efficiency of microsilica have also been reported with a major finding that, there is a potential to increase the use of recycled coarse aggregate from recommended 30% to 50% with the incorporation of microsilica without any cause for alarm. The underlisted are recommended for further studies in order to boost the use of recycled coarse aggregate in concrete by incorporating microsilica in the mix.

1) The recycled aggregate used in the study was obtained from one source. However the impurities from construction and demolition debris varies from a source to the

other and it is suggested that further research should be conducted to assess the effect(s) of these impurities from various sources on the engineering properties of recycled aggregate concrete;

2) The engineering properties of the concrete produced were investigated up till 28 days. However, further research should be carried out at a later curing age in order to understand the behaviour of these materials more with time than the reported curing age;
3) The use of Scanning Electron Microscope (SEM) to identify and provide evidence of the effect of microsilica addition in interaction with the pore structure and hydrated cement of recycled aggregate concrete;
4) It will be useful to carry out some numerical analysis to model the behaviour of the fibre reinforced prism to cyclic loadings.
5) The combination of these materials should be used in concrete for structural application that requires high strength and high durability. Although care should be taken if required in applications where creep is a governing factor or consideration to design.
6) The use of recycled fines should also be considered as a partial replacement for natural fine aggregate in concrete.

APPENDICES

Appendix 1: Sample calculations of design mix

Table 66: Sample calculation of concrete design mix – Series 1 (Reference)

Design mix of concrete {100% N.A - 0% R.C.A } control

Stage	Item	Values				
1	1.1 Characteristic Strength		Specified	N/mm²	**50**	at 28days
			Proportion Defective		**5**	%
	1.2 Standard Deviation	Fig 3		Less than 20 results s=	**8**	N/mm²
		5% defective		k (Sec 4.4 p12)=	**1.64**	
	1.3 Margin	**CI**		M=k*s	**13.1**	N/mm²
		or specified				N/mm²
	1.4 Target Mean strength	**C2**		fm=fc+M	**63.1**	N/mm²
	1.5 Cement Type	Specified		Ordinary Portant Cement		
	1.6 aggregate Type: Coarse : Fine			Crushed(100%)＋Uncrushed(0%)		N/mm²
	1.7 Free-water/Cement ratio	Table2, Fig 4	0.37	Use the lower Value		
	1.8 Maximum Free-Water/Cement ratio	Specified	0.5		**0.37**	
2	2.1 Slump or Vebe time	Specified	Slump	**60~180mm**	Vebe time	**0-3 s**
	2.2 Maximum Aggregate Size	Specified	Crushed(100%)＋Uncrushed(0%)		**10 mm**	mm
	2.3 Free-water Content	Table3	(see pfa sheet) table 9B	Wwater=	**230**	kg/m³
3	3.1 Cement content C3	C= Free-water contenet/free-water/cement ratio			**583**	kg/m³
	3.2 Maximum Cement content	Specified				kg/m³
	3.3 Minimum Cement content	Specified				kg/m³
			use3.1 if〉 3.2			
			use3.3 if〉 3.1			kg/m³
4	4.1 Relative Density of aggregate (SSD)		**2.6**			
	4.2 Concrete Density	Fig 5		D=	**2320**	kg/m³
	4.3 Total Aggregate content	C4		Aggregate=D-C-W	**1507.0**	kg/m³
5	5.1 Grading of Fine Aggregate	See table 20 of thesis		Percentage Passing 600㎛ sieve=	**74**	%(calculated)
	5.2 Proportion of Fine Aggregate	Fig 6			**40**	%
	5.3 Fine Aggregate content			Fine=Total aggregate*Proportion of fine=	**602.8**	kg/m³
	5.4 coarse Aggregate content C5			Total aggregate-Fine aggregate=	**904.2**	kg/m³
6	**Quantities(kg)**	**Cement**	**Water**	**Fine Aggregate**	**Coarse Aggregate (10mm)**	
					Natural 100%	**Recycled 0%**
	6.1 Per m³ (based on SSD, Moisture content of SSD was compared with that of Oven Dry)	**583.0**	**230.0**	**602.8**	**904.2**	**0.0**
	Absorption of Aggregate (constant) fine; 1.67%, natural coarse; 1.44% @ (SSD)			**1.67**	**1.44**	
	6.2 Per m³ (based on Oven dry)	**583.0**	**252.7**	**592.9**	**891.4**	
	6.3 per m³(based on Air dry : moisture content of Air Dry was compared with that of Oven dry)					
	Absorption of Aggregate (variable) fine; 3.22%, natural coarse; 6.0% @ (Air dry)			**3.22**	**6.00**	
		583.0	**176.1**	**612.6**	**948.3**	**0.0**
	6.4 Per volume of 0.072㎥ required	**42.0**	**12.7**	**44.1**	**68.3**	**0.0**

Table 67: Sample calculation of concrete design mix – Series 1

Design mix of concrete {75%N.A - 25%R.C.A}

Stage	Item	Values				
1	1.1 Characteristic Strength		Specified	N/㎟	**50**	at 28days
			Proportion Defective		**5**	%
	1.2 Standard Deviation	Fig 3		Less than 20 results s=	**8**	N/㎟
		5% defective		k (Sec 4.4 p12)=	**1.64**	
	1.3 Margin	**CI**		M=k*s	**13.1**	N/㎟
		or specified				N/㎟
	1.4 Target Mean strength	**C2**		fm=fc+M	**63.1**	N/㎟
	1.5 Cement Type	Specified		Ordinary Portant Cement		
	1.6 aggregate Type: Coarse : Fine		Crushed(100%)＋Uncrushed(0%)			N/㎟
	1.7 Free-water/Cement ratio	Table2, Fig 4	0.37	Use the lower Value		
	1.8 Maximum Free-Water/ Cement ratio	Specified	0.5		**0.37**	
2	2.1 Slump or Vebe time	Specified	Slump	**60~180mm**	Vebe time	**0-3 s**
	2.2 Maximum Aggregate Size	Specified	Crushed(100%)＋Uncrushed(0%)		**10 mm**	mm
	2.3 Free-water Content	Table3		Wwater=	**230**	kg/m³
3	3.1 Cement content C3	C= Free-water contenet/free-water/cement ratio			**583**	kg/m³
	3.2 Maximum Cement content	Specified				kg/m³
	3.3 Minimum Cement content	Specified				kg/m³
			use3.1 if〉 3.2			
			use3.3 if〉 3.1			kg/m³
	3.4 Modified free-water/ cement ratio					kg/m³
4	4.1 Relative Density of aggregate (SSD)		**2.6**			
	4.2 Concrete Density	Fig 5		D=	**2320**	kg/m³
	4.3 Total Aggregate content	C4		Aggregate=D-C-W	**1507.0**	kg/m³
5	5.1 Grading of Fine Aggregate	See table 20 of thesis		Percentage Passing 600㎛ sieve=	**74**	%(calculated)
	5.2 Proportion of Fine Aggregate	Fig 6			**40**	%
	5.3 Fine Aggregate content			Fine=Total aggregate*Proportion of fine=	**602.8**	kg/m³
	5.4 coarse Aggregate content C5			Total aggregate-Fine aggregate=	**904.2**	kg/m³

6	**Quantities(kg)**	**Cement**	**Water**	**Fine Aggregate**	**Coarse Aggregate (10mm)**	
					Natural 75%	**Recycled 25%**
	6.1 Per ㎥ (based on SSD, Moisture content of SSD was compared with that of Oven Dry)	**583.0**	**230.0**	**602.8**	**678.15**	**226.05**
	Absorption of Aggregate (constant) fine; 1.67%, natural coarse; 1.44%, recycled coarse agg; 7.65 @ (SSD)			**1.67**	**1.44**	**7.65**
	6.2 Per ㎥ (based on Oven dry)	**583.0**	**249.5**	**592.9**	**668.5**	**210.0**
	6.3 per ㎥(based on Air dry : moisture content of Air Dry was compared with that of Oven dry)					
	Absorption of Aggregate (variable) fine; 13.3%, natural coarse; 5.2 % , recycled coarse agg; 6.9% @ (Air dry)			**13.30**	**5.20**	**6.90**
		583.0	**106.3**	**683.9**	**705.2**	**225.5**
	6.4 Per volume of 0.072㎥ required	**42.0**	**7.7**	**49.2**	**50.8**	**16.2**

Table 68: Sample calculation of concrete design mix – Series 2 (Reference)

Design mix of concrete {100% N.A - 0% R.C.A - 4.45kg/m³ Fibre}							
Stage	Item	Values					
1	1.1 Characteristic Strength		Specified	N/mm²	**50**	at 28days	
			Proportion Defective		**5**	%	
	1.2 Standard Deviation	Fig 3		Less than 20 results s=	**8**	N/mm²	
		5% defective		k (Sec 4.4 p12)=	**1.64**		
	1.3 Margin	**CI**		M=k*s	**13.1**	N/mm²	
		or specified				N/mm²	
	1.4 Target Mean strength	**C2**		fm=fc+M	**63.1**	N/mm²	
	1.5 Cement Type	Specified		Ordinary Portant Cement			
	1.6 aggregate Type: Coarse : Fine		Crushed(100%)＋Uncrushed(0%)			N/mm²	
	1.7 Free-water/Cement ratio	Table2, Fig 4	0.37	Use the lower Value			
	1.8 Maximum Free-Water/Cement ratio	Specified	0.5		**0.37**		
2	2.1 Slump or Vebe time	Specified	Slump	**60~180mm**	Vebe time	**0-3 s**	
	2.2 Maximum Aggregate Size	Specified	Crushed(100%)＋Uncrushed(0%)		**10 mm**	mm	
	2.3 Free-water Content	Table3	(see pfa sheet) table 9B	Wwater=	**230**	kg/m³	
3	3.1 Cement content C3	C= Free-water contenet/free-water/cement ratio			**583**	kg/m³	
	3.2 Maximum Cement content	Specified				kg/m³	
	3.3 Minimum Cement content	Specified				kg/m³	
			use3.1 if〉3.2				
			use3.3 if〉3.1			kg/m³	
4	4.1 Relative Density of aggregate (SSD)		**2.6**				
	4.2 Concrete Density	Fig 5		D=	**2320**	kg/m³	
	4.3 Total Aggregate content	C4		Aggregate=D-C-W	**1507.0**	kg/m³	
5	5.1 Grading of Fine Aggregate	See table 20 of thesis	Percentage Passing 600㎛ sieve=		**74**	%(calculated)	
	5.2 Proportion of Fine Aggregate	Fig 6			**40**	%	
	5.3 Fine Aggregate content		Fine=Total aggregate*Proportion of fine=		**602.8**	kg/m³	
	5.4 coarse Aggregate content C5		Total aggregate-Fine aggregate=		**904.2**	kg/m³	
6	**Quantities(kg)**	**Cement**	**Water**	**Fine Aggregate**	**Coarse Aggregate (10mm)**		**Synthetic Macro Fibre**
					Natural 100%	**Recycled 0%**	
	6.1 Per m³ (based on SSD, Moisture content of SSD was compared with that of Oven Dry)	**583.0**	**230.0**	**602.8**	**904.2**	**0.0**	**4.45**
	Absorption of Aggregate (constant) fine; 1.67%, natural coarse; 1.44% @ (SSD)			**1.67**	**1.44**		
	6.2 Per m³ (based on Oven dry)	**583.0**	**252.7**	**592.9**	**891.4**		
	6.3 per m³(based on Air dry : moisture content of Air Dry was compared with that of Oven dry)						
	Absorption of Aggregate (variable) fine; 7.8%, natural coarse; 5.9% @ (Air dry)			**7.80**	**5.90**		
		583.0	**146.7**	**643.1**	**947.3**	**0.0**	**4.45**
	6.4 Per volume of 0.072m³ required	**42.0**	**10.6**	**46.3**	**68.2**	**0.0**	**0.32**

Table 69: Sample calculation of concrete design mix – Series 2

Design mix of concrete {50%N.A - 50%R.C.A - 4.45kg/m^3 Fibre}							
Stage	Item	Values					
1	1.1 Characteristic Strength		Specified	N/㎟	**50**	at 28days	
			Proportion Defective		**5**	%	
	1.2 Standard Deviation	Fig 3		Less than 20 results s=	**8**	N/㎟	
		5% defective		k (Sec 4.4 p12)=	**1.64**		
	1.3 Margin	**CI**		M=k*s	**13.1**	N/㎟	
		or specified				N/㎟	
	1.4 Target Mean strength	**C2**		fm=fc+M	**63.1**	N/㎟	
	1.5 Cement Type	Specified		Ordinary Portant Cement			
	1.6 aggregate Type: Coarse : Fine		Crushed(100%)＋Uncrushed(0%)			N/㎟	
	1.7 Free-water/Cement ratio	Table2, Fig 4	0.37	Use the lower Value			
	1.8 Maximum Free-Water/Cement ratio	Specified	0.5		**0.37**		
2	2.1 Slump or Vebe time	Specified	Slump	**60~180mm**	Vebe time	**0-3 s**	
	2.2 Maximum Aggregate Size	Specified	Crushed(100%)＋Uncrushed(0%)		**10 mm**	mm	
	2.3 Free-water Content	Table3		Wwater=	**230**	kg/m^3	
3	3.1 Cement content C3	C= Free-water contenet/free-water/cement ratio			**583**	kg/m^3	
	3.2 Maximum Cement content	Specified				kg/m^3	
	3.3 Minimum Cement content	Specified				kg/m^3	
			use3.1 if〉 3.2				
			use3.3 if〉 3.1			kg/m^3	
	3.4 Modified free-water/cement ratio					kg/m^3	
4	4.1 Relative Density of aggregate (SSD)		**2.6**				
	4.2 Concrete Density	Fig 5		D=	**2320**	kg/m^3	
	4.3 Total Aggregate content	C4		Aggregate=D-C-W	**1507.0**	kg/m^3	
5	5.1 Grading of Fine Aggregate	See table 20 of thesis	Percentage Passing 600㎛ sieve=		**74**	%(calculated)	
	5.2 Proportion of Fine Aggregate	Fig 6			**40**	%	
	5.3 Fine Aggregate content		Fine=Total aggregate*Proportion of fine=		**602.8**	kg/m^3	
	5.4 coarse Aggregate content C5		Total aggregate-Fine aggregate=		**904.2**	kg/m^3	
	Quantities(kg)	Cement	Water	Fine Aggregate	Coarse Aggegate **10 mm**		
		583.0	**230.0**	**602.8**	**904.2**		
6	**Quantities(kg)**	**Cement**	**Water**	**Fine Aggregate**	**Coarse Aggregate (10mm)** **Natural 50%**	**Recycled 50%**	**Synthetic Macro Fibre**
	6.1 Per m^3 (based on SSD, Moisture content of SSD was compared with that of Oven Dry)	**583.0**	**230.0**	**602.8**	**452.1**	452.10	4.45
	Absorption of Aggregate (constant) fine; 1.67%, natural coarse; 1.44% , recycled coarse: 7.65 @ (SSD)			**1.67**	**1.44**	**7.65**	
	6.2 Per m^3 (based on Oven dry)	**583.0**	**246.3**	**592.9**	**445.7**	**420.0**	
	6.3 per m^3(based on Air dry : moisture content of Air Dry was compared with that of Oven dry)						
	Absorption of Aggregate (variable) fine; 7.8%, natural coarse; 5.9 % , recycled coarse 8% @ (Air dry)			**7.80**	**5.90**	**8.00**	
		583.0	**131.7**	**643.1**	**473.6**	**456.5**	
	6.4 Per volume of 0.072m^3 required	**42.0**	**9.5**	**46.3**	**34.1**	**32.9**	**0.32**

Table 70: Sample calculation of concrete design mix – Series 3 (Reference)

Design mix of concrete {100% N.A - 0% R.C.A - 4.45kg/m³ Fibre}							
Stage	Item	Values					
1	1.1 Characteristic Strength		Specified	N/㎟	**50**	at 28days	
			Proportion Defective		**5**	%	
	1.2 Standard Deviation	Fig 3		Less than 20 results s=	**8**	N/㎟	
		5% defective		k (Sec 4.4 p12)=	**1.64**		
	1.3 Margin	**CI**		M=k*s	**13.1**	N/㎟	
		or specified				N/㎟	
	1.4 Target Mean strength	**C2**		fm=fc+M	**63.1**	N/㎟	
	1.5 Cement Type	Specified		Ordinary Portant Cement			
	1.6 aggregate Type: Coarse : Fine		Crushed(100%)＋Uncrushed(0%)			N/㎟	
	1.7 Free-water/Cement ratio	Table2, Fig 4	0.37	Use the lower Value			
	1.8 Maximum Free-Water/Cement ratio	Specified	0.5		**0.37**		
2	2.1 Slump or Vebe time	Specified	Slump	**60~180mm**	Vebe time	**0-3 s**	
	2.2 Maximum Aggregate Size	Specified	Crushed(100%)＋Uncrushed(0%)		**10 mm**	mm	
	2.3 Free-water Content	Table3	(see pfa sheet) table 9B	Wwater=	**230**	kg/m³	
3	3.1 Cement content C3	C= Free-water contenet/free-water/cement ratio			**583**	kg/m³	
	3.2 Maximum Cement content	Specified				kg/m³	
	3.3 Minimum Cement content	Specified				kg/m³	
			use3.1 if〉 3.2				
			use3.3 if〉 3.1			kg/m³	
4	4.1 Relative Density of aggregate (SSD)		**2.6**				
	4.2 Concrete Density	Fig 5		D=	**2320**	kg/m³	
	4.3 Total Aggregate content	C4		Aggregate=D-C-W	**1507.0**	kg/m³	
5	5.1 Grading of Fine Aggregate	See table 20 of thesis		Percentage Passing 600㎛ sieve=	**74**	%(calculated)	
	5.2 Proportion of Fine Aggregate	Fig 6			**40**	%	
	5.3 Fine Aggregate content			Fine=Total aggregate*Proportion of fine=	**602.8**	kg/m³	
	5.4 coarse Aggregate content C5			Total aggregate-Fine aggregate=	**904.2**	kg/m³	
6	**Quantities(kg)**	**Cement**	**Water**	**Fine Aggregate**	**Coarse Aggregate (10mm)**		**Synthetic Macro Fibre**
					Natural 100%	**Recycled 0%**	
	6.1 Per ㎥ (based on SSD, Moisture content of SSD was compared with that of Oven Dry)	**583.0**	**230.0**	**602.8**	**904.2**	**0.0**	**1.00**
	Absorption of Aggregate (constant) fine; 1.67%, natural coarse; 1.44% @ (SSD)			**1.67**	**1.44**		
	6.2 Per ㎥ (based on Oven dry)	**583.0**	**252.7**	**592.9**	**891.4**		
	6.3 per ㎥(based on Air dry : moisture content of Air Dry was compared with that of Oven dry)						
	Absorption of Aggregate (variable) fine; 7.0%, natural coarse; 4.8% @ (Air dry)			**7.00**	**4.80**		
		583.0	**163.2**	**637.5**	**936.3**	**0.0**	**1.00**
	6.4 Per volume of 0.072㎥ required	**42.0**	**11.7**	**45.9**	**67.4**	**0.0**	**0.07**

Table 71: Sample calculation of concrete design mix – Series 3

Design mix of concrete {0%N.A - 100%R.C.A - 1kg/m^{3}F}							
Stage	Item	Values					
1	1.1 Characteristic Strength		Specified	N/㎟	**50**	at 28days	
			Proportion Defective		**5**	%	
	1.2 Standard Deviation	Fig 3		Less than 20 results s=	**8**	N/㎟	
		5% defective		k (Sec 4.4 p12)=	**1.64**		
	1.3 Margin	**CI**		M=k*s	**13.1**	N/㎟	
		or specified				N/㎟	
	1.4 Target Mean strength	**C2**		fm=fc+M	**63.1**	N/㎟	
	1.5 Cement Type	Specified		Ordinary Portant Cement			
	1.6 aggregate Type: Coarse : Fine		Crushed(100%)＋Uncrushed(0%)			N/㎟	
	1.7 Free-water/Cement ratio	Table2, Fig 4	0.37	Use the lower Value			
	1.8 Maximum Free-Water/ Cement ratio	Specified	0.5		**0.37**		
2	2.1 Slump or Vebe time	Specified	Slump	**60~180mm**	Vebe time	**0-3 s**	
	2.2 Maximum Aggregate Size	Specified	Crushed(100%)＋Uncrushed(0%)		**10 mm**	mm	
	2.3 Free-water Content	Table3		Wwater=	**230**	kg/㎥	
3	3.1 Cement content C3	C= Free-water contenet/free-water/cement ratio			**583**	kg/㎥	
	3.2 Maximum Cement content	Specified				kg/㎥	
	3.3 Minimum Cement content	Specified				kg/㎥	
			use3.1 if〉 3.2				
			use3.3 if〉 3.1			kg/㎥	
	3.4 Modified free-water/ cement ratio					kg/㎥	
4	4.1 Relative Density of aggregate(SSD)		**2.6**				
	4.2 Concrete Density	Fig 5		D=	**2320**	kg/㎥	
	4.3 Total Aggregate content	C4		Aggregate=D-C-W	**1507.0**	kg/㎥	
5	5.1 Grading of Fine Aggregate	See table 20 of thesis		Percentage Passing 600㎛ sieve=	**74**	%(calculated)	
	5.2 Proportion of Fine Aggregate	Fig 6			**40**	%	
	5.3 Fine Aggregate content			Fine=Total aggregate*Proportion of fine=	**602.8**	kg/㎥	
	5.4 coarse Aggregate content C5			Total aggregate-Fine aggregate=	**904.2**	kg/㎥	
	Quantities(kg)	Cement	Water	Fine Aggregate	Coarse Aggegate		
					10 mm		
		583.0	**230.0**	**602.8**	**904.2**		
6	**Quantities(kg)**	**Cement**	**Water**	**Fine Aggregate**	**Coarse Aggregate (10mm)**		**Synthetic Macro Fibre kg/m^3**
					Natural 0%	**Recycled 100%**	
	6.1 Per ㎥ (based on SSD, Moisture content of SSD was compared with that of Oven Dry)	**583.00**	**230.00**	**602.80**	**0.0**	**904.20**	**1.00**
	Absorption of Aggregate (constant) fine; 1.67%, natural coarse; 1.44% , recycled agg. 7.65 @ (SSD)			**1.67**	**0.00**	**7.65**	
	6.2 Per ㎥ (based on Oven dry)	**583.0**	**304.2**	**592.9**	**0.0**	**839.9**	
	6.2..1 Per volume of 0.072㎥ required	**39.7**	**20.7**	**40.4**	**0.0**	**57.2**	
	6.3 per ㎥(based on Air dry : moisture content of Air Dry was compared with that of Oven dry)						
	Absorption of Aggregate (variable) fine; 5.2%, natural coarse; 0.0 % , recycled coarse 8.4 @ (Air dry)			**5.20**	**0.00**	**8.40**	
		583.0	**194.6**	**625.4**	**0.0**	**917.0**	
	6.4 Per volume of 0.072㎥ required	**39.7**	**13.3**	**42.6**	**0.0**	**62.5**	**0.07**

Table 72: Sample calculation of concrete design mix – Series 4 (Reference)

Design mix of concrete {100% N.A - 0% RCA - 1kg/m³Fibre - 5%M - 0.4% SP}

1	1.1 Characteristic Strength		Specified	N/㎟	**50**	at 28days			
			Proportion Defective		**5**	%			
	1.2 Standard Deviation	Fig 3		Less than 20 results s=	**8**	N/㎟			
		5% defective		k (Sec 4.4 p12)=	**1.64**				
	1.3 Margin	**C1**		M=k*s	**13.1**	N/㎟			
		or specified				N/㎟			
	1.4 Target Mean strength	**C2**		fm=fc+M	**63.1**	N/㎟			
	1.5 Cement Type	Specified		Ordinary Portant Cement					
	1.6 aggregate Type: Coarse : Fine		Crushed(100%)＋Uncrushed(0%)			N/㎟			
	1.7 Free-water/Cement ratio	Table2, Fig 4	0.37	Use the lower Value					
	1.8 Maximum Free-Water/ Cement ratio	Specified	0.5		**0.37**				
2	2.1 Slump or Vebe time	Specified	Slump	**60~180mm**	Vebe time	**0-3 s**			
	2.2 Maximum Aggregate Size	Specified	Crushed(100%)＋Uncrushed(0%)		**10 mm**	mm			
	2.3 Free-water Content	Table3		Wwater=	**230**	kg/㎥			
3	3.1 Cement content C3	C= Free-water contenet/free-water/cement ratio			**583**	kg/㎥			
	3.2 Maximum Cement content	Specified				kg/㎥			
	3.3 Minimum Cement content	Specified				kg/㎥			
			use3.1 if〉3.2						
			use3.3 if〉3.1			kg/㎥			
	3.4 Modified free-water/ cement ratio					kg/㎥			
4	4.1 Relative Density of aggregate(SSD)		**2.6**						
	4.2 Concrete Density	Fig 5		D=	**2320**	kg/㎥			
	4.3 Total Aggregate content	C4		Aggregate=D-C-W	**1507.0**	kg/㎥			
5	5.1 Grading of Fine Aggregate	See table 20 of thesis	Percentage Passing 600㎛ sieve=		**74**	%(calculated)			
	5.2 Proportion of Fine Aggregate	Fig 6			**40**	%			
	5.3 Fine Aggregate content		Fine=Total aggregate*Proportion of fine=		**602.8**	kg/㎥			
	5.4 coarse Aggregate content C5		Total aggregate-Fine aggregate=		**904.2**	kg/㎥			
	Quantities(kg)	Cement	Water	Fine Aggregate	Coarse Aggegate				
					10 mm				
		583.0	**230.0**	**602.8**	**904.2**				
6	**Quantities(kg)**	**Cement**	**Water**	**Fine Aggregate**	**Coarse Aggregate (10mm)**		**Synthetic Macro Fibre**	**Microsilica 5%**	**Super-plasticizer 0.4%**
					Natural 100%	**Recycled 0%**			
	6.1 Per ㎥ (based on SSD, Moisture content of SSD was compared with that of Oven Dry)	**583.00**	**230.00**	**602.80**	**904.2**	**0.00**	**1.00**	**29.20**	**2.33**
	Absorption of Aggregate (constant) fine; 1.67%, natural coarse; 1.44%, @ (SSD)			**1.67**	**1.44**	**0**			
	6.2 Per ㎥ (based on SSD)	**583.0**	**252.7**	**592.9**	**891.4**	**0.0**			
	6.3 per ㎥(based on Air dry : moisture content of Air Dry was compared with that of Oven dry)								
	Absorption of Aggregate (variable) fine; 1.03%, natural coarse;1.2 % @ (Air dry)			**1.03**	**1.20**	0.00			
		583.0	**235.7**	**599.1**	**902.2**	**0.0**	**1.00**	**29.20**	**2.33**
	6.4 Per volume of 0.072㎥ required	**42.0**	**17.0**	**43.1**	**65.0**	**0.0**	**0.07**	**2.10**	**0.17**

Table 73: Sample calculation of concrete design mix – Series 5 (Reference

Design mix of concrete {100% N.A - 0% RCA - 1kg/m³Fibre - 10%M - 0.6% SP}									
1	1.1 Characteristic Strength		Specified	N/㎟	**50**	at 28days			
			Proportion Defective		**5**	%			
	1.2 Standard Deviation	Fig 3		Less than 20 results s=	**8**	N/㎟			
		5% defective		k (Sec 4.4 p12)=	**1.64**				
	1.3 Margin	**C1**		M=k*s	**13.1**	N/㎟			
		or specified				N/㎟			
	1.4 Target Mean strength	**C2**		fm=fc+M	**63.1**	N/㎟			
	1.5 Cement Type	Specified		Ordinary Portant Cement					
	1.6 aggregate Type: Coarse : Fine		Crushed(100%)＋Uncrushed(0%)			N/㎟			
	1.7 Free-water/Cement ratio	Table2, Fig 4	0.37	Use the lower Value					
	1.8 Maximum Free-Water/ Cement ratio	Specified	0.5		**0.37**				
2	2.1 Slump or Vebe time	Specified	Slump	**60~180mm**	Vebe time	**0-3 s**			
	2.2 Maximum Aggregate Size	Specified	Crushed(100%)＋Uncrushed(0%)		**10 mm**	mm			
	2.3 Free-water Content	Table3		Wwater=	**230**	kg/㎥			
3	3.1 Cement content C3	C= Free-water contenet/free-water/cement ratio			**583**	kg/㎥			
	3.2 Maximum Cement content	Specified				kg/㎥			
	3.3 Minimum Cement content	Specified				kg/㎥			
			use3.1 if〉 3.2						
			use3.3 if〉 3.1			kg/㎥			
	3.4 Modified free-water/ cement ratio					kg/㎥			
4	4.1 Relative Density of aggregate(SSD)		**2.6**						
	4.2 Concrete Density	Fig 5		D=	**2320**	kg/㎥			
	4.3 Total Aggregate content	C4		Aggregate=D-C-W	**1507.0**	kg/㎥			
5	5.1 Grading of Fine Aggregate	See table 20 of thesis	Percentage Passing 600㎛ sieve=		**74**	%(calculated)			
	5.2 Proportion of Fine Aggregate	Fig 6			**40**	%			
	5.3 Fine Aggregate content		Fine=Total aggregate*Proportion of fine=		**602.8**	kg/㎥			
	5.4 coarse Aggregate content C5		Total aggregate-Fine aggregate=		**904.2**	kg/㎥			
	Quantities(kg)	Cement	Water	Fine Aggregate	Coarse Aggegate				
					10 mm				
		583.0	**230.0**	**602.8**	**904.2**				
6	**Quantities(kg)**	**Cement**	**Water**	**Fine Aggregate**	**Coarse Aggregate (10mm)**		**Synthetic Macro Fibre**	**Microsilica 10%**	**Super-plasticizer 0.6%**
					Natural 100%	**Recycled 0%**			
	6.1 Per ㎥ (based on SSD, Moisture content of SSD was compared with that of Oven Dry)	**583.00**	**230.00**	**602.80**	**904.2**	**0.00**	**1.00**	**58.40**	**3.50**
	Absorption of Aggregate (constant) fine; 1.67%, natural coarse; 1.44%, @ (SSD)			**1.67**	**1.44**	**0**			
	6.2 Per ㎥ (based on SSD)	**583.0**	**252.7**	**592.9**	**891.4**	**0.0**			
	6.3 per ㎥(based on Air dry : moisture content of Air Dry was compared with that of Oven dry)								
	Absorption of Aggregate (variable) fine; 1.03%, natural coarse;1.2 % @ (Air dry)			**1.03**	**1.20**	0.00			
		583.0	**235.7**	**599.1**	**902.2**	**0.0**	**1.00**	**58.40**	**3.50**
	6.4 Per volume of 0.072㎥ required	**42.0**	**17.0**	**43.1**	**65.0**	**0.0**	**0.07**	**4.20**	**0.25**

Table 74: Sample calculation of concrete design mix – Series 6 (Reference)

	Design mix of concrete {100% N.A - 0% RCA - 1kg/m^3Fibre - 15%M - 0.8% SP}								
1	1.1 Characteristic Strength		Specified	N/㎟	**50**	at 28days			
			Proportion Defective		**5**	%			
	1.2 Standard Deviation	Fig 3		Less than 20 results s=	**8**	N/㎟			
		5% defective		k (Sec 4.4 p12)=	**1.64**				
	1.3 Margin	**C1**		M=k*s	**13.1**	N/㎟			
		or specified				N/㎟			
	1.4 Target Mean strength	**C2**		fm=fc+M	**63.1**	N/㎟			
	1.5 Cement Type	Specified		Ordinary Portant Cement					
	1.6 aggregate Type: Coarse : Fine			Crushed(100%)＋Uncrushed(0%)		N/㎟			
	1.7 Free-water/Cement ratio	Table2, Fig 4	0.37	Use the lower Value					
	1.8 Maximum Free-Water/ Cement ratio	Specified	0.5		**0.37**				
2	2.1 Slump or Vebe time	Specified	Slump	**60~180mm**	Vebe time	**0-3 s**			
	2.2 Maximum Aggregate Size	Specified	Crushed(100%)＋Uncrushed(0%)		**10 mm**	mm			
	2.3 Free-water Content	Table3		Wwater=	**230**	kg/m^3			
3	3.1 Cement content C3	C= Free-water contenet/free-water/cement ratio			**583**	kg/m^3			
	3.2 Maximum Cement content	Specified				kg/m^3			
	3.3 Minimum Cement content	Specified				kg/m^3			
			use3.1 if〉 3.2						
			use3.3 if〉 3.1			kg/m^3			
	3.4 Modified free-water/ cement ratio					kg/m^3			
4	4.1 Relative Density of aggregate(SSD)		**2.6**						
	4.2 Concrete Density	Fig 5		D=	**2320**	kg/m^3			
	4.3 Total Aggregate content	C4		Aggregate=D-C-W	**1507.0**	kg/m^3			
5	5.1 Grading of Fine Aggregate	See table 20 of thesis		Percentage Passing 600㎛ sieve=	**74**	%(calculated)			
	5.2 Proportion of Fine Aggregate	Fig 6			**40**	%			
	5.3 Fine Aggregate content			Fine=Total aggregate*Proportion of fine=	**602.8**	kg/m^3			
	5.4 coarse Aggregate content C5			Total aggregate-Fine aggregate=	**904.2**	kg/m^3			
	Quantities(kg)	Cement	Water	Fine Aggregate	Coarse Aggegate				
					10 mm				
		583.0	**230.0**	**602.8**	**904.2**				
6	**Quantities(kg)**	**Cement**	**Water**	**Fine Aggregate**	**Coarse Aggregate (10mm)**		**Synthetic Macro Fibre**	**Microsilica 15%**	**Super-plasticizer 0.8%**
					Natural 100%	**Recycled 0%**			
	6.1 Per m^3 (based on SSD, Moisture content of SSD was compared with that of Oven Dry)	**583.00**	**230.00**	**602.80**	**904.2**	**0.00**	**1.00**	**87.60**	**4.66**
	Absorption of Aggregate (constant) fine; 1.67%, natural coarse; 1.44%, @ (SSD)			**1.67**	**1.44**	**0**			
	6.2 Per m^3 (based on SSD)	**583.0**	**252.7**	**592.9**	**891.4**	**0.0**			
	6.3 per m^3(based on Air dry : moisture content of Air Dry was compared with that of Oven dry)								
	Absorption of Aggregate (variable) fine; 1.03%, natural coarse;1.2 % @ (Air dry)			**1.03**	**1.20**	0.00			
		583.0	**235.7**	**599.1**	**902.2**	**0.0**	**1.00**	**87.60**	**4.66**
	6.4 Per volume of 0.072 m^3 required	**42.0**	**17.0**	**43.1**	**65.0**	**0.0**	**0.07**	**6.31**	**0.34**

Table 75: Sample calculation of concrete design mix – Series 7 (Reference)

Design mix of concrete {100% N.A - 0% RCA - 1kg/m³Fibre - 20%M - 1.1% SP}

1	1.1 Characteristic Strength		Specified	N/㎟	50	at 28days			
			Proportion Defective		5	%			
	1.2 Standard Deviation	Fig 3		Less than 20 results s=	8	N/㎟			
		5% defective		k (Sec 4.4 p12)=	1.64				
	1.3 Margin	C1		M=k*s	13.1	N/㎟			
		or specified				N/㎟			
	1.4 Target Mean strength	C2		fm=fc+M	63.1	N/㎟			
	1.5 Cement Type	Specified		Ordinary Portant Cement					
	1.6 aggregate Type: Coarse : Fine		Crushed(100%)＋Uncrushed(0%)			N/㎟			
	1.7 Free-water/Cement ratio	Table2, Fig 4	0.37	Use the lower Value					
	1.8 Maximum Free-Water/ Cement ratio	Specified	0.5		0.37				
2	2.1 Slump or Vebe time	Specified	Slump	60~180mm	Vebe time	0-3 s			
	2.2 Maximum Aggregate Size	Specified	Crushed(100%)＋Uncrushed(0%)		10 mm	mm			
	2.3 Free-water Content	Table3		Wwater=	230	kg/m³			
3	3.1 Cement content C3	C= Free-water contenet/free-water/cement ratio			583	kg/m³			
	3.2 Maximum Cement content	Specified				kg/m³			
	3.3 Minimum Cement content	Specified				kg/m³			
			use3.1 if〉 3.2						
			use3.3 if〉 3.1			kg/m³			
	3.4 Modified free-water/ cement ratio					kg/m³			
4	4.1 Relative Density of aggregate(SSD)		2.6						
	4.2 Concrete Density	Fig 5		D=	2320	kg/m³			
	4.3 Total Aggregate content	C4		Aggregate=D-C-W	1507.0	kg/m³			
5	5.1 Grading of Fine Aggregate	See table 20 of thesis	Percentage Passing 600㎛ sieve=		74	%(calculated)			
	5.2 Proportion of Fine Aggregate	Fig 6			40	%			
	5.3 Fine Aggregate content		Fine=Total aggregate*Proportion of fine=		602.8	kg/m³			
	5.4 coarse Aggregate content C5		Total aggregate-Fine aggregate=		904.2	kg/m³			
	Quantities(kg)	Cement	Water	Fine Aggregate	Coarse Aggegate 10 mm				
		583.0	230.0	602.8	904.2				
6	**Quantities(kg)**	**Cement**	**Water**	**Fine Aggregate**	**Coarse Aggregate (10mm)** **Natural 100%**	**Recycled 0%**	**Synthetic Macro Fibre**	**Microsilica 20%**	**Super-plasticizer 1.1%**
	6.1 Per m³ (based on SSD, Moisture content of SSD was compared with that of Oven Dry)	583.00	230.00	602.80	904.2	0.00	1.00	116.80	6.41
	Absorption of Aggregate (constant) fine; 1.67%, natural coarse; 1.44%, @ (SSD)			1.67	1.44	0			
	6.2 Per m³ (based on SSD)	583.0	252.7	592.9	891.4	0.0			
	6.3 per m³(based on Air dry : moisture content of Air Dry was compared with that of Oven dry)								
	Absorption of Aggregate (variable) fine; 1.03%, natural coarse;1.2 % @ (Air dry)			1.03	1.20	0.00			
		583.0	235.7	599.1	902.2	0.0	1.00	116.80	6.41
	6.4 Per volume of 0.072m³ required	42.0	17.0	43.1	65.0	0.0	0.07	8.41	0.46

Appendix 2: Particle Density and Water Absorption

1) Natural Fine Aggregate (Sand) -- Pyknometer method

A	B	C	D	E	F	G	H
(M1) Weight of SSD Aggregate in air (g)	(M2) Apparent weight of Pyknometer + wet sample (g)	(M3) Apparent weight of Pyknometer + water (g)	(M4) Weight of oven-dried sample in air (g)	ρ_a (kg/m³) Apparent particle density	ρ_{rd} (kg/m³) Particle density on an oven-dried basis	ρ_{ssd} (kg/m³) Particle density on a SSD basis	Water Absorption (%)
1806.8	2654.1	1652.2	1777.2	2292.27	2207.98	2445.00	1.67

2) Natural Coarse Aggregate (Gravel) – Wire basket method

A	B	C	D	E	F	G	H
(M1) Weight of SSD Aggregate in air (g)	(M2) Apparent weight of basket in water + SSD sample (g)	(M3) Apparent weight of empty basket in water (g)	(M4) Weight of oven-dried sample in air (g)	ρ_a (kg/m³) Apparent particle density	ρ_{rd} (kg/m³) Particle density on an oven-dried basis	ρ_{ssd} (kg/m³) Particle density on a SSD basis	Water Absorption (%)
1522	2566.7	1652.2	1500.4	2560.85	2469.79	2505.35	1.44

3) Natural Fine Aggregate (Sand) – Wire basket method

A	B	C	D	E	F	G	H
(M1) Weight of SSD Aggregate in air (g)	(M2) Apparent weight of basket in water + SSD sample (g)	(M3) Apparent weight of empty basket in water (g)	(M4) Weight of oven-dried sample in air (g)	ρ_a (kg/m³) Apparent particle density	ρ_{rd} (kg/m³) Particle density on an oven-dried basis	ρ_{ssd} (kg/m³) Particle density on a SSD basis	Water Absorption (%)
1340.7	2415.7	1652.2	1245.4	2584.35	2157.66	2322.77	7.65

Appendix 3: Strength tests results on hardened concrete

Compressive Strength Test

Table 76: Result of Compressive strength test at 0% recycled coarse aggregate content

Concrete series type.	**Days**		
	1	**7**	**28**
	Compressive strength (MPa)		
Series 1	24.20	43.50	53.86
Series 2	22.10	40.90	51.53
Series 3	23.40	42.50	52.40
Series 4	36.80	54.30	71.15
Series 5	38.70	57.20	84.84
Series 6	42.60	62.60	86.46
Series 7	40.20	60.20	85.82

Table 77: Result of Compressive strength test at 25% recycled coarse aggregate content

Concrete series type.	**Days**		
	1	**7**	**28**
	Compressive strength (MPa)		
Series 1	22.80	40.55	50.06
Series 2	20.00	37.44	48.13
Series 3	21.70	38.90	48.90
Series 4	30.50	53.60	68.40
Series 5	33.10	55.40	71.00
Series 6	38.40	58.70	77.85
Series 7	35.70	57.60	75.91

Table 78: Result of Compressive strength test at 50% recycled coarse aggregate content

Concrete series type.	Days		
	1	7	28
	Compressive strength (MPa)		
Series 1	20.28	37.18	47.26
Series 2	17.73	32.92	44.10
Series 3	19.10	35.10	45.80
Series 4	24.70	50.20	63.40
Series 5	28.80	53.10	65.20
Series 6	33.00	56.40	75.74
Series 7	30.80	54.00	71.88

Table 79: Result of Compressive strength test at 75% recycled coarse aggregate content

Concrete series type.	Days		
	1	7	28
	Compressive strength (MPa)		
Series 1	17.03	29.02	44.53
Series 2	13.31	25.61	40.20
Series 3	15.90	27.20	43.00
Series 4	22.80	47.20	55.90
Series 5	25.50	49.20	63.98
Series 6	30.10	53.10	74.53
Series 7	28.40	51.90	69.68

Table 80: Result of Compressive strength test at 100% recycled coarse aggregate content

Concrete series type.	Days		
	1	**7**	**28**
	Compressive strength (MPa)		
Series 1	13.10	28.42	41.00
Series 2	10.16	22.23	36.10
Series 3	12.20	25.60	38.70
Series 4	22.60	44.90	53.90
Series 5	24.10	46.30	59.30
Series 6	27.30	50.20	68.78
Series 7	25.60	48.50	65.54

Tensile Splitting Strength Test

Table 81: Result of Tensile Splitting strength test at 0% recycled coarse aggregate content

Concrete series type.	Days		
	1	**7**	**28**
	Tensile splitting strength (MPa)		
Series 1	2.29	2.76	3.32
Series 2	3.33	3.70	4.01
Series 3	2.51	2.90	3.46
Series 4	3.00	3.45	3.84
Series 5	3.35	3.80	5.52
Series 6	3.44	3.95	5.76
Series 7	3.40	3.86	5.70

Table 82: Result of Tensile Splitting strength test at 25% recycled coarse aggregate content

Concrete series type.	Days		
	1	7	28
	Tensile splitting strength (MPa)		
Series 1	1.89	2.50	2.98
Series 2	3.25	3.55	3.92
Series 3	2.05	2.59	3.15
Series 4	2.85	3.38	3.81
Series 5	3.11	3.65	4.17
Series 6	3.41	3.84	4.84
Series 7	3.37	3.76	4.47

Table 83: Result of Tensile Splitting strength test at 50% recycled coarse aggregate content

Concrete series type.	Days		
	1	7	28
	Tensile splitting strength (MPa)		
Series 1	1.38	1.90	2.54
Series 2	2.85	3.46	3.76
Series 3	1.61	2.20	2.78
Series 4	2.42	3.18	3.48
Series 5	3.02	3.53	3.97
Series 6	3.21	3.70	4.71
Series 7	3.10	3.61	4.38

Table 84: Result of Tensile Splitting strength test at 75% recycled coarse aggregate content

Concrete series type.	Days		
	1	**7**	**28**
	Tensile splitting strength (MPa)		
Series 1	1.16	1.48	2.01
Series 2	2.36	3.29	3.71
Series 3	1.40	1.80	2.29
Series 4	2.10	3.14	3.50
Series 5	2.36	3.25	3.64
Series 6	2.66	3.63	4.50
Series 7	2.47	3.47	4.25

Table 85: Result of Tensile Splitting strength test at 100% recycled coarse aggregate content

Concrete series type.	Days		
	1	**7**	**28**
	Tensile splitting strength (MPa)		
Series 1	0.70	1.23	1.87
Series 2	1.95	3.17	3.48
Series 3	0.88	1.41	2.00
Series 4	1.73	2.98	3.35
Series 5	1.86	3.13	3.52
Series 6	2.32	3.41	4.34
Series 7	2.18	3.30	4.17

Flexural Strength Test

Table 86: Result of Flexural strength test at 0% recycled coarse aggregate content

Concrete series type.	**Days**		
	1	**7**	**28**
	Flexural strength (MPa)		
Series 1	3.55	5.00	7.10
Series 2	4.30	6.27	8.70
Series 3	3.80	5.39	7.63
Series 4	4.50	7.00	9.13
Series 5	5.13	7.30	9.40
Series 6	5.86	8.00	10.30
Series 7	5.60	7.60	9.85

Table 87: Result of Flexural strength test at 25% recycled coarse aggregate content

Concrete series type.	**Days**		
	1	**7**	**28**
	Flexural strength (MPa)		
Series 1	3.00	4.30	5.80
Series 2	3.92	5.29	7.10
Series 3	3.30	4.67	6.35
Series 4	4.16	5.89	7.50
Series 5	4.61	6.30	7.92
Series 6	5.50	7.20	9.00
Series 7	4.97	6.94	8.30

Table 88: Result of Flexural strength test at 50% recycled coarse aggregate content

Concrete series type.	Days		
	1	**7**	**28**
	Flexural strength (MPa)		
Series 1	2.33	3.67	4.55
Series 2	3.18	4.55	5.84
Series 3	2.85	4.00	4.81
Series 4	3.75	5.06	6.40
Series 5	4.00	5.53	6.80
Series 6	5.00	6.60	8.20
Series 7	4.45	5.85	7.75

Table 89: Result of Flexural strength test at 75% recycled coarse aggregate content

Concrete series type.	Days		
	1	**7**	**28**
	Flexural strength (MPa)		
Series 1	1.87	2.93	4.00
Series 2	2.77	4.00	4.91
Series 3	2.38	3.20	4.38
Series 4	3.20	4.75	5.70
Series 5	3.66	5.00	6.00
Series 6	4.35	6.00	7.50
Series 7	3.98	5.57	6.88

Table 90: Result of Flexural strength test at 100% recycled coarse aggregate content

Concrete series type.	Days		
	1	**7**	**28**
	Flexural strength (MPa)		
Series 1	1.24	2.17	3.12
Series 2	2.32	3.40	4.40
Series 3	1.70	2.77	3.66
Series 4	2.88	3.90	5.40
Series 5	3.05	4.10	5.52
Series 6	3.97	5.40	6.94
Series 7	3.42	4.85	6.00

APPENDIX 4: Durability performance of concrete

Table 91: Water permeability test result at 5% Microsilica

√Time (Minutes ½)	Volume of flow (m³)				
	RCA-0%	RCA-25%	RCA-50%	RCA-75%	RCA-100%
0.00	1.00E-09	1.00E-09	1.00E-09	1.00E-09	1.00E-09
1.00	5.00E-08	8.50E-08	1.26E-07	1.43E-07	3.75E-07
1.41	5.60E-08	1.20E-07	1.59E-07	1.89E-07	4.61E-07
1.73	6.00E-08	1.46E-07	1.71E-07	2.23E-07	5.32E-07
2.00	6.40E-08	1.69E-07	1.82E-07	2.50E-07	5.63E-07
2.24	6.90E-08	1.80E-07	2.15E-07	2.65E-07	5.87E-07
2.45	7.60E-08	1.94E-07	2.30E-07	2.80E-07	6.04E-07
2.65	8.10E-08	2.10E-07	2.45E-07	3.00E-07	6.17E-07
2.83	8.60E-08	2.25E-07	2.60E-07	3.15E-07	6.32E-07
3.00	9.00E-08	2.30E-07	2.72E-07	3.26E-07	6.43E-07
3.16	9.50E-08	2.36E-07	2.80E-07	3.35E-07	6.54E-07
3.32	1.01E-07	2.40E-07	2.89E-07	3.43E-07	6.64E-07
3.46	1.04E-07	2.45E-07	2.95E-07	3.50E-07	6.73E-07
3.61	1.08E-07	2.51E-07	3.01E-07	3.56E-07	6.80E-07
3.74	1.11E-07	2.55E-07	3.07E-07	3.60E-07	6.88E-07
3.87	1.15E-07	2.60E-07	3.10E-07	3.64E-07	6.95E-07

Table 92: Water permeability test result at 10% Microsilica

√Time (Minutes ½)	Volume of flow (m³)				
	RCA-0%	RCA-25%	RCA-50%	RCA-75%	RCA-100%
0.00	1.00E-09	1.00E-09	1.00E-09	1.00E-09	1.00E-09
1.00	4.00E-08	9.60E-08	8.90E-08	7.40E-08	1.75E-07
1.41	4.60E-08	1.22E-07	1.15E-07	9.80E-08	3.00E-07
1.73	5.00E-08	1.39E-07	1.30E-07	1.15E-07	3.70E-07
2.00	5.40E-08	1.50E-07	1.55E-07	1.28E-07	4.00E-07
2.24	5.90E-08	1.67E-07	1.98E-07	2.25E-07	4.20E-07
2.45	6.40E-08	1.76E-07	2.06E-07	2.50E-07	4.35E-07
2.65	6.80E-08	1.85E-07	2.12E-07	2.75E-07	4.48E-07
2.83	7.60E-08	1.92E-07	2.18E-07	2.87E-07	4.57E-07
3.00	8.00E-08	1.99E-07	2.25E-07	2.98E-07	4.70E-07
3.16	8.40E-08	2.06E-07	2.30E-07	3.08E-07	4.82E-07
3.32	8.70E-08	2.10E-07	2.37E-07	3.14E-07	4.90E-07
3.46	9.20E-08	2.15E-07	2.42E-07	3.20E-07	4.97E-07
3.61	9.60E-08	2.19E-07	2.48E-07	3.26E-07	5.04E-07
3.74	1.00E-07	2.22E-07	2.53E-07	3.30E-07	5.08E-07
3.87	1.03E-07	2.25E-07	2.58E-07	3.33E-07	5.12E-07

Table 93: Water permeability test result at 15% Microsilica

√Time (Minutes ½)	Volume of flow (m³)				
	RCA-0%	RCA-25%	RCA-50%	RCA-75%	RCA-100%
0.00	1.00E-09	3.00E-09	1.00E-09	1.00E-09	1.00E-09
1.00	2.70E-08	3.10E-08	4.20E-08	4.80E-08	9.10E-08
1.41	3.00E-08	3.30E-08	4.80E-08	6.10E-08	1.19E-07
1.73	3.20E-08	3.50E-08	5.00E-08	6.80E-08	1.33E-07
2.00	3.50E-08	4.20E-08	5.30E-08	7.40E-08	1.43E-07
2.24	4.00E-08	5.50E-08	6.40E-08	9.20E-08	1.52E-07
2.45	4.60E-08	5.90E-08	7.20E-08	1.07E-07	1.67E-07
2.65	5.10E-08	6.20E-08	8.80E-08	1.18E-07	1.80E-07
2.83	5.50E-08	6.90E-08	9.60E-08	1.27E-07	2.00E-07
3.00	6.00E-08	7.30E-08	1.04E-07	1.38E-07	2.12E-07
3.16	6.60E-08	7.70E-08	1.10E-07	1.44E-07	2.20E-07
3.32	7.10E-08	8.50E-08	1.16E-07	1.50E-07	2.31E-07
3.46	7.70E-08	9.00E-08	1.23E-07	1.56E-07	2.40E-07
3.61	8.30E-08	9.40E-08	1.27E-07	1.61E-07	2.46E-07
3.74	8.90E-08	9.80E-08	1.32E-07	1.65E-07	2.50E-07
3.87	9.30E-08	1.02E-07	1.37E-07	1.70E-07	2.53E-07

Table 94: Water permeability test result at 20% Microsilica

√Time (Minutes ½)	Volume of flow (m³)				
	RCA-0%	RCA-25%	RCA-50%	RCA-75%	RCA-100%
0.00	1.00E-09	3.00E-09	1.00E-09	1.00E-09	3.00E-09
1.00	3.20E-08	3.70E-08	5.00E-08	7.60E-08	9.40E-08
1.41	3.70E-08	4.20E-08	6.10E-08	9.40E-08	1.17E-07
1.73	4.30E-08	4.60E-08	6.60E-08	1.11E-07	1.45E-07
2.00	4.80E-08	5.00E-08	7.20E-08	1.20E-07	1.45E-07
2.24	5.30E-08	5.60E-08	7.40E-08	1.01E-07	1.86E-07
2.45	5.70E-08	6.00E-08	8.00E-08	1.15E-07	1.99E-07
2.65	6.20E-08	6.80E-08	8.80E-08	1.26E-07	2.10E-07
2.83	6.60E-08	7.20E-08	9.40E-08	1.35E-07	2.23E-07
3.00	7.10E-08	7.70E-08	1.00E-07	1.47E-07	2.40E-07
3.16	7.60E-08	8.40E-08	1.06E-07	1.56E-07	2.57E-07
3.32	8.00E-08	9.00E-08	1.13E-07	1.65E-07	2.64E-07
3.46	8.40E-08	9.60E-08	1.18E-07	1.72E-07	2.72E-07
3.61	8.80E-08	1.00E-07	1.22E-07	1.78E-07	2.77E-07
3.74	9.20E-08	1.04E-07	1.27E-07	1.83E-07	2.81E-07
3.87	9.60E-08	1.08E-07	1.32E-07	1.86E-07	2.85E-07

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