Enhancing the Performance of Recycled Aggregate Concrete with Microsilica

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***Abstract*—Recycled aggregate was used as replacement for crushed gravel between 0-100% with an increment of 25%. Synthetic macro fibre and microsilica were added to some of the concrete mixes to improve their mechanical properties. The control mix was designed to have a 28-day characteristic cube strength of 50MPa, water/cement ratio of 0.39 and high workability (60-180 mm). Physical (slump) and mechanical (compressive strength, flexural strength, splitting tensile strength, and modulus of elasticity) tests were conducted on fresh and 660 hardened concrete samples respectively. The aim was to investigate the use of higher percentages of recycled aggregate than the current 20% level recommended by BS 8500. Results show reduction in the physical and mechanical properties with increasing recycled aggregate content. Addition of synthetic macro fibre had no significant effect on the concrete compressive strength. However, the concretes with synthetic macro fibre had higher flexural strength, splitting tensile strength, and elastic modulus compared with those without synthetic macro fibre. Addition of 5% microsilica to the mix with 50% recycled coarse aggregate produced a 28-day compressive strength slightly higher than the target mean compressive strength of 63MPa. This result suggests that there is a potential for increasing the optimum fraction of recycled coarse aggregate in concrete from 20% to 50%.**

***Index Terms*—microsilica, workability, permeability, synthetic macro fibre, compressive strength, splitting tensile strength**

I. Introduction

The increasing demand for infrastructure due to the continuous population growth, and the high rate of urbanisation, have led to increased consumption of concrete, which is currently the second most widely consumed resource in the world after water [1]. Although concrete can be a cost effective material with superior strength and durability properties, the continuous use of natural aggregates in conventional concrete has serious environmental and economic consequences as it can lead to the depletion of natural resources (aggregate), increasing disposal problems and significant energy consumption in quarrying activities. The partial or full substitution of natural aggregate by recycled coarse aggregate retrieved from demolition debris is a favourable alternative to mitigate the environmental and economic effects of using natural aggregates.

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Extensive research has been conducted on recycled concrete after its properties were first investigated by Gluzhge in 1946 [2]. Significant progress has been made in the past few decades thanks to modern sustainable concrete technology which has led to the current use of recycled coarse aggregate in non-structural concrete applications such as embankment fills, low-grade concrete production, coarse materials for road sub-base, and paving blocks. In spite of the large number of conducted research studies, there is still a room for improving the physical and mechanical properties of recycled aggregate concrete. This will help reduce the current high level of uncertainty associated with the structural use of the material.

This study examines the effect of synthetic macro fibre and microsilica on the physical and mechanical properties of recycled aggregate concrete. The aim of the study is to investigate the use of higher percentages of recycled aggregates than the currently recommended 20% level [3] without negatively impacting the physical and mechanical properties.

II. Materials and Mix Design

A. Materials

The materials used in the experimental investigation are shown in Table I.

TABLE I. MATERIALS

Materials	Description
Cement	CEM II/B-V 32,5N (Rugby Portland - fly ash cement)
Synthetic macro fibre	54mm Forta- Ferro, Virgin copolymer/polypropylene, Specific gravity of 0.91, tensile strength 570-660MPa
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

B. Concrete Mix Design

Four concrete mix series (see Table II–Table V) were designed according to the UK Building Research Establishment (BRE) method. Each series contained five

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concrete mixes. The 28-day characteristic cube strength, water/cement ratio and workability class were 50 MPa, 0.39 and high respectively. A total of 660 concrete samples at Saturated Surface Dry (SSD) state were investigated.

TABLE II. SERIES I CONCRETE MIX (CONTROL MIX)

Recycle 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 kg/m³)	0	0	0	0	0
Microsilica (kg/m³)	0	0	0	0	0
Superplasticiser (kg/m³)	0	0	0	0	0

TABLE III. SERIES II CONCRETE MIX

Recycle 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 (kg/m³)	0	0	4.5	4.5	4.5
Microsilica (kg/m³)	0	0	0	0	0
Superplasticiser (kg/m³)	0	0	0	0	0

TABLE IV. SERIES III CONCRETE MIX

Recycle 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 (kg/m³)	1	1	1	1	1
Microsilica (kg/m³)	0	0	0	0	0
Superplasticiser (kg/m³)	0	0	0	0	0

TABLE V. SERIES IV CONCRETE MIX

Recycle 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 (kg/m³)	1	1	1	1	1
Microsilica (kg/m³)	29.2	29.2	29.2	29.2	29.2
Superplasticiser (kg/m³)	2.33	2.33	2.33	2.33	2.33

C. Concrete Mixing and Placing

Winget Croker Cumflow RP50XD Rotating Pan concrete mixer was used for the concrete mixing. Half of the fine aggregate (sand) quantity was placed at the bottom of the mixer pan followed by cement which was subsequently covered with the remaining half of the fine aggregate. These materials were dry mixed for 30 seconds (s) after which the entire quantity of natural and recycled coarse aggregates were added respectively and thoroughly dry mixed for another 30s to ensure a well-blended concrete mixture. Synthetic macro fibres were added during the mixing in order to ensure even dispersion of fibres. Free-water was gradually added to the mix materials in the mixer and the mixing was further done for about 90s. After ascertaining consistency, the concrete was placed in various lubricated moulds (cubes, cylinders, prisms) in three layers with each layer 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 24 hours to prevent early loss of moisture. The concrete samples were thereafter de-moulded and cured in the water tank at about 20 ℃.

III. EXPERIMENTAL INVESTIGATION

Series of laboratory tests were performed in order to investigate (i) the effect of different percentages (higher than 20%) of recycled coarse aggregate as substitute for natural coarse aggregate and (ii) the effect of microsilica on the mechanical and physical properties of concrete.

A. Particle Density and Water Absorption

The test procedure to determine the particle densities and water absorption rates of fine aggregate, natural and recycled coarse aggregates was conducted in accordance to [4]. These tests were conducted under Saturated Surface Dry (SSD) and Oven Dry (OD) states, respectively. The Pyknometer method was employed for sand while the Wire Basket method was used for crushed gravel and recycled coarse aggregate respectively. The water absorption was calculated using the relationship;

$$W_a = [(\rho_{ssd} - \rho_{od}) / \rho_{od}] \times 100\% \quad (1)$$

where W_a is the water absorption (%), ρ_{ssd} is the particle saturated surface dry density, and ρ_{od} is the particle oven dry density.

B. Slump Test

The workability of the fresh concrete was measured in accordance to [5] using the standard apparatus for every batch of mixes to indicate consistency. The apparatus used were slump cone mould, flat non-absorbent horizontal base plate, and steel tamping rod. The mould was filled in three layers with freshly prepared concrete, and each layer received 25 blows using tamping rod. The slump value in millimetre was measured and recorded as the vertical difference between the highest point at the centre of the subsided (slumped) concrete and the top of the mould.

C. Compressive Strength Test

Compressive strength test was conducted at 28 days to determine the maximum stress on concrete cube samples at failure. Three standard 100×100×100 mm^3 cube samples were prepared for each concrete mix in Series 1 – 4 and tested to failure using a digital Avery-Denison compression testing machine. The test was conducted in accordance to [6].

The mean of the maximum loads at failure for the three samples were recorded and the compressive strength was determined from the relationship;

$$f_{cu} = F/A \quad (2)$$

where f_{cu} is the cube compressive strength (MPa), F is the mean of the maximum loads at failure (N), and A is the cross sectional area of the cube sample (mm^2).

D. Flexural Strength Test

Three standard 100×100×500 mm^3 hardened concrete prism samples were prepared for each concrete mix in Series 1 - 4 and tested to failure at 28 days in order to determine the flexural strength of the concrete samples. The test complied with [7] using a third-point loading arrangement. The mean maximum load at failure for three samples was recorded. The flexural strength was calculated from the relationship:

$$f_{bt} = FL/bd^2 \quad (3)$$

where f_{bt} is the flexural strength (MPa), F is the mean maximum load at failure (N), L is the distance between the supporting rollers (mm), and b and d are the width and depth of the prism (mm) respectively.

E. Splitting Tensile Strength Test

This test was conducted in accordance with [8] on hardened cylindrical concrete samples (100 mm diameter × 200 mm long). Three samples were prepared for each concrete mix in Series 1 to 4 and tested to failure at 28 days in order to obtain the indirect tensile strength of the samples.

The maximum load at failure was recorded and the mean splitting tensile strength was obtained using the equation:

$$f_{ct} = 2F/\pi dL \quad (4)$$

where f_{ct} is the splitting tensile strength (MPa), F is the average maximum load at failure (N), d is the diameter of the cylinder (mm), and L is the length of the line of contact of the sample (mm).

F. Static Modulus of Elasticity

Static Elastic Modulus test was conducted in accordance to [9] on hardened cylindrical concrete samples (100 mm diameter × 200 mm long). Three samples were prepared for each concrete mix in series 1 - 4 and tested to failure at 28 days in order to determine the static modulus of elasticity in compression.

G. Permeability Test (Autoclam)

Permeability test was carried out in order to determine the water permeability index of hardened concrete. The permeability index characterises the durability properties of concrete. Three 100×100×100 mm^3 cube samples were prepared for each concrete mix in series 1 - 4 and tested using the AutoClam permeability test system. The concrete cube samples were stored for a week after removal from the curing tank in order to ensure that the samples are sufficiently dry before the permeability test was performed.

The test was conducted for 15 minutes and the flow was recorded automatically by an electronic controller. The cumulative volume of water absorbed into the concrete at different pressures was plotted against the square root of time between the 5th and 15th minutes as recommended. The gradient of the linear graph was taken as the permeability (sorptivity) index.

IV. Results and Discussion

A. Particle Density and Water Absorption

Table VI shows particle density and water absorption results for the natural and recycled aggregates used in the experimental investigation.

TABLE VI. Results of Particle Density and Water Absorption

Aggregate	Crushed Gravel	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 (%)	1.42	10.73	7.65

The particle density results of the recycled coarse aggregate under saturated surface dry and oven dry conditions were 2323 kg/m^3 and 2158 kg/m^3 respectively. These results are 7.3% and 12.6% lower than the corresponding particle density results of the crushed gravel aggregate which were 2505 kg/m^3 and 2470 kg/m^3 respectively. The lower density results may be attributable to the low density of old mortar adhered to the recycled coarse aggregate particles. A similar explanation was suggested by [10] and [11], and both studies linked the lower density of recycled aggregate to the light weight and porous nature of the mortar attached to the parent aggregates.

The water absorption for the recycled coarse aggregate and crushed gravel was 7.65% and 1.42% respectively. This result implies that the recycled aggregate water absorption is about 5.4 times higher than that of the crushed gravel. It has been reported [12], [13] that recycled aggregate water absorption is 3-5 times higher than that of crushed gravel, and this was attributed to the relatively high porosity of the cement paste attached to the recycled concrete aggregate.

TABLE VII. Results of Slump Test

RCA (%)	Series 1 (mm)	Series 2 (mm)	Series 3 (mm)	Series 4 (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

B. Slump Values

The results of the workability test are given in Table VII. Except for Series 2, the slump results are within the specified range of 60-180 mm [5].

The slump results for Series 1 indicate that the maximum slump value of 115 mm was measured for the concrete with 0% recycled coarse aggregate content. The minimum slump value of 69 mm, which represents 40% reduction from the maximum value of 115 mm, was recorded for the concrete with 100% recycled coarse aggregate content. Similar trends were observed for Series 2, 3 and 4. However, for Series 1, the higher water absorption of the recycled coarse aggregate was responsible for the reduction in slump values [14], [15].

The additional reduction in Series 4 workability, compared to that of Series 1, was due to the large surface area of the microsilica particles, and was mitigated by the addition of the superplasticiser in order to meet the specified workability requirements [5]. Reduction in workability of concrete with increasing proportion of microsilica was also reported elsewhere [16].

The additional reduction in Series 2 slump values, compared to the corresponding values for Series 1, was due to the addition of a 0.50% fibre dosage. This rendered the concrete mix less workable due to the large surface area of the synthetic macro fibre which resulted in an increased amount of mortar and entrapped air being entangled around the aggregate particles. Comparable results have been reported [17], [18] where concrete mixes with high fibre dosage had low workability due to interlocking of fibre and entrapped air. This led to reduction in cement hydration due to insufficient free-water. The low workability and dryness of recycled coarse aggregate caused difficulty in compaction and surface finish of the concrete.

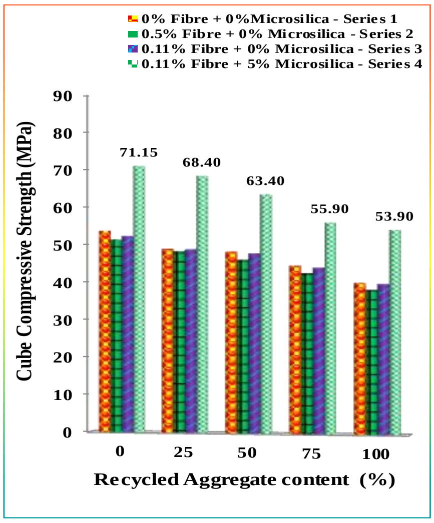

Figure 1. Results of 28-day compressive strength

C. Compressive Strength Results

Fig. 1 presents the 28-day cube compressive strength results for each of the concrete mixes. It was observed from the results of Series 1, 2, and 3 that the control mix with 0% recycled coarse aggregate content had the maximum compressive strengths of 54 MPa, 52 MPa, and 52 MPa respectively. The results show that the concrete mixes without macro fibre (Series 1) had slightly higher compressive strength results than the corresponding mixes with macro fibre (Series 2 and 3). Given that the differences in compressive strength between Series 1 and Series 2 and 3 were less than 5%, it can be concluded that the inclusion of the 54 mm forta-ferro synthetic macro fibre did not significantly affect the compressive strength of concrete. This result confirms the findings of other researchers [19]-[21].

For Series 4 which contained synthetic macro fibre and microsilica, the concrete mixes with 0, 25, and 50% recycled coarse aggregate had compressive strengths of 71.2 MPa, 68.4 MPa, and 63.4 MPa respectively, which are all higher than the target mean compressive strength of 63 MPa. These values represent increases of about 32, 27, and 18% respectively compared with the reference concrete mix in Series 1. This result is important because it suggests that there is a potential for increasing the optimum fraction of recycled coarse aggregate in concrete from 20% to 50%. The substitution of crushed gravel by recycled coarse aggregate at 75% yielded about 4% strength gain whereas at 100% substitution the strength was comparable to that of the reference mix.

For a given recycled coarse aggregate content, the addition of 5% microsilica significantly improved the concrete compressive strength. This result is attributable to the densifying properties and pozzolanic action of microsilica which had smaller particle size than cement particles. Of note is that an increase of more than 25% in concrete compressive strength was reported when microsilica was added to concrete [22]. The strength 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.

Generally, it can be concluded that the concrete compressive strength decreased with the increase in Recycled Coarse Aggregate (RCA) percentage in the mix. This observation was also reported by [23] and [24] and both studies attributed the results to higher porosity which weakened the recycled coarse aggregate.

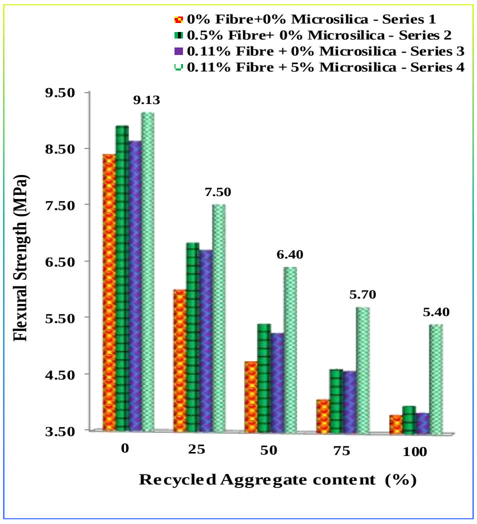

Figure 2. Results of 28-day flexural strength

D. *Flexural Strength Results*

The 28-day flexural strength results are illustrated in Fig. 2. For a given percentage of recycled coarse aggregate, the concrete mixes in Series 1 (control), which included neither synthetic macro fibre nor microsilica, had the lowest flexural strengths. At 25, 50, 75, and 100% replacement levels, the mixes with 0.11% synthetic macro fibre and 5% microsilica (Series 4) had flexural strengths that were 12, 25, 28, and 29% respectively higher than the corresponding mixes in Series 1. This was due to the ductile behaviour of the synthetic macro fibre and their role in reducing and bridging cracks before failure. Comparable results and explanation were reported elsewhere [25].

The addition of microsilica significantly enhanced the flexural strengths of the concrete mixes in Series 4 compared with those of the corresponding mixes in Series 3. Comparable results have been reported elsewhere [26].

Generally, it can be concluded that the concrete flexural strength increased with increasing percentages of macro fibre and microsilica but decreased with increasing percentage of recycled coarse aggregate. Comparable findings were reported elsewhere [25]-[27].

E. *Splitting Tensile Strength Results*

Splitting tensile strength results at 28 days are given in Fig. 3.

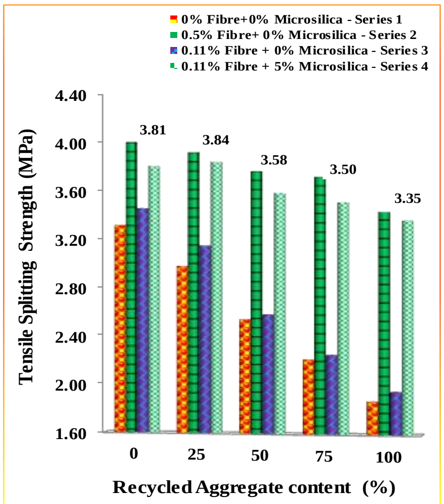

Figure 3. Results of 28-day splitting tensile strength

The splitting tensile strength decreased with the increase in percentage of recycled aggregate in all the concrete mixes. This observation correlates with the strength reduction pattern reported by [28] which was attributed to the porous nature of the recycled aggregate.

Synthetic macro fibre addition at 0.5% volume fraction in Series 2 improved the 28-day splitting tensile strength by approximately 24, 32, 40, and 45% for the concrete mixes with 25, 50, 75, and 100% recycled coarse aggregate content respectively when compared with the corresponding mixes in Series 1. This increase may be attributable to the role of the macro fibre in preventing early cracking. This trend agrees with the findings reported by [29].

The concrete mixes in Series 4 with 25, 50, 75, and 100% recycled aggregate content had splitting tensile strengths that were 22, 29, 37, and 44% higher respectively than that of the control mix in Series 1. These results were achieved due to the combined effects of the synthetic macro fibre and microsilica. The role of the synthetic macro fibre in strength enhancement has been mentioned above. Microsilica improves the microstructure of the interfacial transition zone and increases the bond strength between the new cement paste and the recycled aggregate [30].

F. *Static Modulus of Elasticity*

Static modulus of elasticity results at 28 days are illustrated in Fig. 4. Overall, the results indicate a reduction in the elastic modulus values with the increase in percentage of recycled coarse aggregate. For Series 1, 2, and 3; the concrete mixes containing 100% recycled coarse aggregate had elastic moduli that were 49, 44, and 46% respectively lower than the elastic moduli of the corresponding concrete mixes with 0% recycled coarse aggregate.

Comparable results were reported elsewhere [31]-[33]. This was due to the lower elastic modulus of the recycled coarse aggregate when compared with that of the crushed gravel.

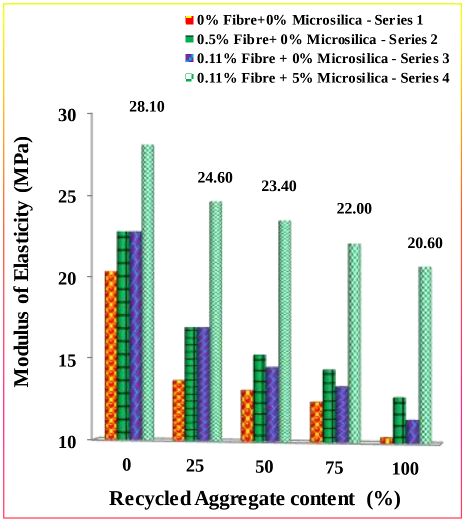

Figure 4. Static modulus of elasticity results at 28 days

For a given percentage of recycled aggregate, results from Series 2 and 3 containing synthetic macro fibre show higher elastic modulus values in comparison with the results of Series 1. The concrete samples with macro fibre and microsilica (Series 4) had the highest elastic modulus whereas those without macro fibre and microsilica (Series 1) had the lowest elastic modulus. At 100% replacement level, the elastic modulus of Series 4 mix was 42% higher than that of Series 1 mix.

G. *Permeability Results*

Table VIII presents the water permeability test results. It was generally observed that the higher the percentage of recycled coarse aggregate, the higher the permeability indices and vice-versa. This may be attributable to the porous nature of the recycled coarse aggregate which increases water permeability.

TABLE VIII. 28-DAY WATER PERMEABILITY (AUTOCLAM) RESULTS

Mix Id	Recycled Aggregate (%)				
	0	25	50	75	100
Permeability Index ($m^3 \times 10^{-7}/\sqrt{min}$)					
Series 1	0.7	1.4	2.3	3.8	4.3
Series 2	0.6	0.8	1.0	1.1	1.4
Series 3	0.6	0.9	1.2	1.4	1.7
Series 4	0.3	0.5	0.6	0.6	0.7

For a given percentage of recycled aggregate, Series 1 mix had the highest permeability index whereas Series 4 mix had the least permeability index.

According to Table IX, the mixes in Series 2-4 fall under the very good protective property category. The mixes in Series 1 also fall under the same category apart from the concrete mixes with 75% and 100% recycled aggregate content which fall under the good protective property category. The latter two mixes had permeability indices of 3.8 and 4.3×10^{-7} $m^3/\sqrt{min}$ respectively. The high water absorption of the old mortar attached to the recycled coarse aggregate was responsible for the high permeability results. It has been suggested that the residual mortar acts like a conduit for water transport [34]. Comparable results and explanation were reported elsewhere [35]-[37].

TABLE IX. PROTECTIVE QUALITY OF CONCRETE

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

The concrete mixes in Series 4 had the best durability properties as a result of the incorporation of 5% microsilica which reduced the rate of water inflow to the concrete through its micro-filler effect. It has been reported that addition of microsilica reduced permeability due to its densifying effect on microstructure thereby reducing porosity which subsequently produced denser concrete [38].

V. CONCLUSIONS

Workability, compressive strength, flexural strength, splitting tensile strength, modulus of elasticity, and permeability tests were conducted on recycled aggregate concrete. The aim of the study is to investigate the use of higher percentages of recycled aggregate than the current level of 20% recommended by BS 8500. The main conclusions are as follows:

1) The particle density of recycled coarse aggregate was lower than that of natural coarse aggregate due to the low density of the old mortar attached to the recycled aggregate. The water absorption of recycled coarse aggregate was about 5.4 times higher than that of the natural coarse aggregate due to existence of larger pores in recycled aggregate;
2) The physical and mechanical properties of concrete decreased with increasing percentage of recycled coarse aggregate;
3) Addition of synthetic macro fibre had no significant effect on the concrete compressive strength. However, the concretes with synthetic macro fibre had higher flexural strength, splitting tensile strength, and elastic modulus compared with those without synthetic macro fibre;
4) Addition of 5% microsilica significantly improved the compressive strength, splitting tensile strength, flexural strength, static modulus of elasticity, and water permeability irrespective of the percentage of recycled coarse aggregate in the mix;
5) Addition of 5% microsilica to the mix with 50% recycled coarse aggregate produced a 28-day compressive strength slightly higher than the target mean compressive strength of 63MPa. This result suggests that there is a potential for increasing the optimum fraction of recycled coarse aggregate in concrete from 20% to 50%.

These findings could lead to a step change in the conservation of quarries and reduction in cost of construction materials, and reduce pressure on landfills.

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