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EXPERIMENTAL INVESTIGATION ON SUSTAINABLE FIBROUS LIGHTWEIGHT LECA-BASED CONCRETE WITH FINE RECYCLED AGGREGATES

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ABSTRACT: The world is moving towards the use of sustainable concrete due to its ability to reduce environmental pollution caused by the presence of waste arising from the demolishing of old buildings or those collapsed as a consequence of earthquakes. The combined effects of fine recycled concrete aggregate (RF), light expanded clay coarse aggregate (LECA), and steel fibres (SF) on the properties of concrete were investigated in the present study. The evaluated properties were slump test, compressive strength, flexural strength, splitting tensile strength, density, and water absorption. The prepared concrete specimens were also evaluated, considering non-destructive tests through ultrasonic pulse velocity and rebound hammer tests. Findings indicated that the inclusion of RF with LECA as a partial and full replacement of gravel in both fibrous and non-fibrous concrete resulted in a drop in compressive, splitting, and flexural strength by an average of 17%, 22%, and 25%, respectively when 50% LECA was used. Furthermore, when 100% LECA was used, the drop became more pronounced, with decreases of 39%, 42%, and 45%, respectively. However, the use of hooked steel fibre at 0.75% compensated for this adverseness, and the strengths of the mixes were generally higher than those of the reference mix, which was produced with normal-weight aggregates.

Keywords: Recycled concrete aggregate, LECA, Hooked steel fibres, Compressive Strength, UPV

1. INTRODUCTION

The advancement of concrete fabrication is becoming increasingly delicate as designers commence integrating specialised concrete into their efforts instead of conventional alternatives. Conventional concretes are characterised by their high density, so the concrete industry has undertaken the development of numerous methodologies to minimise the density and at the same time achieve acceptable characteristics [1]. One of the techniques employed involves the replacement of conventional natural aggregates with lightweight aggregate, thereby yielding numerous advantages, including enhanced thermo-insulation properties and decreased density of the produced concrete [2-5]. Lightweight expanded clay aggregate (LECA) is one type of artificial lightweight aggregate that has gained popularity in civil engineering applications due to its widespread use. LECA finds extensive utility in distinct structural and geotechnical applications owing to its special characteristics. Notably, it serves as an insulation material in civil engineering projects, facilitates efficient drainage, and acts as a lightweight fill in railway systems, road embankments, and various traffic zones. Additionally, it proves valuable as a backfill material for lightweight retaining walls and as a foundation for agricultural and structural applications. Ke et al. [6] found that when the aggregate density was less than 1000 kg/m^3, the aggregate volume fractions significantly impacted the compressive strength and elastic modulus of the lightweight concrete. On the other hand, when the density of the aggregate ranged from 1430 to 1570 kg/m^3, it was seen that the elastic modulus of the concrete dropped as the volume fraction increased. However, no reduction in the compressive strength of the concrete was observed. Nahhab and Ketab [7] concluded that the concrete mixes with a maximum aggregate size of 10 mm had the best flexural and compressive strengths. When it came to flexural strength, the benefits of fibre content were more noticeable than in compressive strength. Here, increasing the aggregate maximum size, amount of fibre, and content of LECA resulted in an adverse effect on the water sorptivity.

Recently, the building industry's usage of natural resources and waste production have been rising dramatically. Construction and demolition waste, on the other hand, have a significant negative influence on the environment. In developing countries, the use of recycled concrete aggregate is growing due to concrete construction demand. In Europe, more than half a billion tons of annual concrete waste are produced, about 325 million and 77 million tons for the US and Japan, respectively. Considering that more than 50% of recyclable materials are utilised in the world's concrete, recycling concrete waste will be very important [8]. More researchers studied the effect of coarse than fine recycled concrete aggregate because of the high porosity of fine recycled aggregate. Because of their high water absorption capacity, recycled aggregates present the main issue when used in concrete buildings. This makes it difficult to control the characteristics of freshly produced concrete, which in turn affects the hardened concrete's strength and durability [9]. To use recycled concrete aggregate (RCA) in concrete, its water absorption needs to be known, and it has to be cleaned from other materials [10]. Nevertheless, it was found that replacing natural aggregates with recycled concrete aggregates (RCA) led to an increase in the compressive strength of concrete because the rough texture of RCA produced better bonding between the cement and aggregate [11, 12]. However, other researchers found that using RCA at 25–30% led to a decrease in compressive strength of about 10–25% [8, 13–15].

On the other hand, plain concrete is a brittle material with low tensile strength and poor fracture toughness. So adding fibres with optimum mechanical properties can improve toughness, increase resistance to fatigue and impact, reduce spalling of the reinforcement cover, and improve abrasion resistance, flexural strength, and shear strength. The fibres modified the failure mechanisms of the composite material by reducing the micro-cracks and changing their mechanics. The outcome of this situation is reliant upon several variables, such as the kind, length, and quantity of fibres; the ratio of water to cementitious materials (w/cm); the ratio of aggregate to binder; the mortar volume; the characteristics of aggregates; and additional parameters related to the mix ingredients. Like conventional concrete, fibres improve the lightweight concrete's ability to withstand high loads while controlling cracks. They additionally improve the concrete's resistance to sudden and dynamic loads, decrease the width of cracks, enhance its tensile strength, and decrease its deformation. However, adding fibres to concrete has a detrimental effect on workability. Gonen [16] studied the effect of steel fibre on the properties of lightweight self-compacting concrete using fly ash, basaltic pumice produced from crushed stone (as lightweight aggregates), and two types of fibre of both high and low carbon content with different amounts of 25 and 50 kg/m^3. He found that the workability of the fresh concrete was adversely impacted by the addition of long fibres. However, the workability remained unaffected upon the addition of short (micro steel) fibres. It is worth mentioning that the addition of steel fibres to concrete significantly improves the tensile and flexural strength of concrete and produces strain-hardening material. Concrete demonstrates strain-hardening characteristics when the steel fibre content reaches or exceeds 0.75%. The flexural strength exhibits a significant enhancement (about 70%), while the first crack load experiences a marginal increase of approximately 11% as the steel fibre content increases from 0.5% to 1.25% [17–18].

From the above-reviewed literature, there has been a major emphasis on individual studies exploring lightweight concrete with the use of LECA, recycled concrete aggregate, and steel fibres. Nonetheless, the combined impact of these variables on the mechanical as well as fresh characteristics of lightweight concrete has not received much attention in the literature, which is the main objective of this research. The properties that were evaluated in the present study included slump testing, compressive strength, flexural strength, splitting tensile strength, density, and water absorption. The concrete specimens were also evaluated using non-destructive tests, including ultrasonic pulse velocity and rebound hammer tests. Despite the lower performance observed when using LECA in combination with RF compared to the reference mixes, this study yielded promising results. The addition of hooked steel fibre assisted in mitigating the negative effects on strength caused by the use of RF and LECA, specifically in terms of splitting tensile strength and flexural strength. The tensile strength of fibrous concrete is even higher than that of the reference mix without fibre.

2. RESEARCH SIGNIFICANCE

Based on the reviewed literature, attention has been paid to the separate studies related to lightweight concrete using LECA, recycled concrete aggregate, and steel fibres. However, limited literature has emphasised the combined effect of these materials on the fresh and mechanical properties of lightweight concrete. It is essential to consider that the compositional variations between normal weight and lightweight concrete have been a matter of concern for researchers, as the latter exhibits inferior fracture behaviour. This might get really problematic if recycled aggregate is used to make lightweight concrete. Consequentially, combining steel fibres with recycled aggregate may be an effective method to develop sustainable structural lightweight concrete.

3. EXPERIMENTAL PROGRAM

3.1 Materials

Ordinary Portland cement (Table 1), produced under the trademark of the Al-Kufa cement factory, was used as a binder for all concrete mixes. It complied with Iraqi specifications [19]. Natural coarse aggregates (Table 2), supplied from Al-Najaf quarries, were rounded gravel with grading and physical properties meeting the requirements of Iraqi Specification [20]. LECA (brought from China) was used in the prepared mixes. The maximum size of the used LECA was 10 mm (Table 3). The water absorption of the LECA was 12%, and the bulk density was 705 kg/m^3. The sieve analysis of LECA complies with the ranges given by ASTM C330 [21]. The recycled fine aggregate, of 4.75 mm maximum size, was obtained by crushing and grinding old concrete so as to obtain a somewhat similar grading of fine aggregates (well-graded sand). In order to reduce the water requirements of the mix as well as to maintain the same workability, super plasticisers (SP) satisfied with ASTM specification C494 / C494M [22] were used in all mixes with different dosages. Here, the dosage of SP of 1.2 and 2.8 (by weight of cement) was respectively added to the non-fibrous and fibrous mixes. Hooked-end steel fibres having length, diameter, aspect ratio, and tensile strength of 30 mm, 0.5 mm, 60, and 1300 MPa were utilised. the volume fraction of the steel fibres used was 0.75%.

Table1: Properties of the used cement

Chemical tests and main compounds		
Oxides	Results	IQS No.5 Limits
CaO%	62.87	-----
SiO_2%	25.03	-----
Al_2O_3%	3.69	-----
Fe_2O_3%	3.21	-----
MgO%	2.34	≤ 5%
SO_3%	1.471	2.8% if C3A >5%
LOI%	1.13	≤ 4%
IR%	1.23	≤ 1.5%
C3S%	47.74	-----
C2S%	29.31	-----
C3A%	2.70	-----
C4AF%	9.55	-----
Physical tests		
Initial setting time	69	≥ 45 min.
Final setting time	6:27	≤ 10 hr.
Fineness (cm^2/g)	3038	≥ 2500
f_{cu} (MPa): 2 days	18.7	≥ 10
f_{cu} (MPa): 28 days	36.4	≥ 32.5

3.2 Mix Proportioning and Testing Methods

The reference mix was designed according to ACI 211.1 [20], such that the first trial mix was adjusted many times in order to reach the target workability and compressive strength. Eight concrete mixes were adopted (Table 4) considering different parameters, including recycled fine aggregate replacement, LECA replacement, and steel fibre inclusion. The ingredients of all the prepared mixes are shown in Table 5. According to the table, C, W, NF, RF, NC, and LW, refer, respectively, to the used cement, water, natural fine aggregates, recycled fine aggregates, natural weight coarse aggregates, and lightweight coarse aggregates. The mixing procedure for normal-weight concrete was as follows: the aggregates were put in the mixer first, and then the cement was added. Thereafter, the dry mixture was mixed for one minute, and then the water with SP was added. The wet mixture was mixed for two minutes. Then the steel fibres (if any) were added and mixed until a homogeneous mixture was achieved.

Table 2: Sieve analysis of NCA

Size (mm)	% Passing by weight	Limits of QS No.5
12.5	100	100
10	100	85-100
5	23	0-25
2.36	0	0-5

Table 3: Sieve analysis of LECA

Size (mm)	% Passing by weight	Limits of ASTM C330
12.5	100	100
10	100	80-100
8	73	---
6	36	---
4.75	19	5-40
2.36	0	0-20

The LECA was immerged in water for at least 48 hours before use because of the high water absorption capacity of this type of lightweight aggregate. The excess water was then drained and the materials weighed. The mixing procedure for lightweight concrete was as follows: in the pan-type mixer, the LECA and sand were blended with 50% of the mixing water for three minutes, then the cement was supplied to the mixer and blended for another 6 minutes. Finally, the remaining water and SP were added to the mixture and mixed for another 6 minutes. A break time of two minutes was taken before pouring the fresh mixes.

Then the steel fibres (if any) were added and mixed until a mixture homogeneity was achieved.

The slump test was used to measure the fresh properties of LWC in accordance with ASTM 143/C 143M [24]. At 28 days, the compressive strength, splitting tensile strength, and flexural strength were tested for the hardened samples of 15 cm cubes, 10 by 20 cm cylinders, and 100 by 100 by 500 prisms, respectively. They were determined according to BS 1881: Part 116 [25], ASTM C496/C496M [26], and ASTM C78 [27], respectively. The ultrasonic pulse velocity through concrete samples was measured at the age of 28 days according to ASTM C597 [28]. The rebound hammer test was also applied to the samples in accordance with ASTM C805 [29].

4. RESULTS AND DISCUSSION

4.1 Fresh Properties

Table 6 illustrates the slump values of all investigated mixes. Obviously, the incorporation of recycled fine aggregate (RF) instead of sand reduced the slump in both fibrous and non-fibrous concrete. Poon et al. [30] pointed out that the main difficulty associated with the use of recycled aggregate is its higher absorption capacity, thus leading to problems in controlling the fresh features of any concrete. However, the inclusion of light expanded clay (LECA) together with RF enhanced the slump values above the reference concrete, and the full substitution of gravel with LECA led to the best slump. On the other hand, the spherical shape of LECA as compared to gravel led to an improvement in the workability of concrete.

4.2 Mechanical Properties

The compressive strength (f_{cu}), flexural strength (f_r), and splitting tensile strength (f_{st}) of non-fibrous and fibrous mixes are shown in Table 6 and Figures 1 and 2. It is obvious from both figures that the best strengths were observed for reference concretes (NC+NF, NC+NF+S), which were produced without recycled fine aggregates (RF) and lightweight aggregate (LECA), followed by mixes with RF (NC+RF, NC+RF+S), mixes with RF and 50% LECA (50LW+RF, 50LW+RF+S), and those with RF and 100% LECA (50LW+RF, 50LW+RF+S). The use of RF reduced the compressive strength, flexural strength, and splitting tensile strength of fibrous and non-fibrous concretes by an average of 10, 14, and 13%, respectively. The mechanical behaviour of the new concrete resulting from recycled concrete aggregate might be a result of the porous interfacial transition zones (ITZ) between aggregates and cement mortar. Many of the foregoing works also evidenced the adverseness of the mechanical features of concrete due to the incorporation of recycled aggregate [31–33].

It is worthwhile to mention that recycled concrete aggregate, derived from waste concrete, comprises mortar-adherent particles in addition to the original particles. Consequently, the newly combined mortar with RCA comprises two ITZs: one is between the original particles and the adhered mortar, and the other is between the new mortar and RCA [34]. This generates weak regions in the microstructure of the new concrete, especially when subjected to bending stresses; thereby, the concrete has a decrease in its flexural strength and fracture energy [35].

Table 4 Designation of the tested mixes

No.	Mix Type	Mix details
1	NC+NF	Natural coarse aggregates+ Natural fine aggregates
2	NC+RF	Natural coarse aggregates+ Recycled fine aggregates
3	50LW+RF	50% LECA+ Recycled fine aggregates
4	100LW+RF	100% LECA+ Recycled fine aggregates
5	NC+NF+S	Natural coarse aggregates+ Natural fine aggregates+ Steel fibres
6	NC+RF+S	Natural coarse aggregates+ Recycled fine aggregates+ Steel fibres
7	50LW+RF+S	50% LECA+ Recycled fine+ Steel fibres aggregates
8	100LW+RF+S	100% LECA+ Recycled fine aggregates+ Steel fibres

Table 5 Mix ingredients (kg/m^3)

Mix	C	W	NF	RF	NC	LW
1	475	190	764	0	910	0
2	475	190	0	625	910	0
3	475	190	0	625	455	110
4	475	190	0	625	0	220
5	475	190	764	0	890	0
6	475	190	0	625	890	0
7	475	190	0	625	445	108
8	475	190	0	625	0	215

Table 6 Fresh and hardened properties of the tested mixes

Mix designation	Slump mm	f_{cu}		f_{st}		f_r		Density kg/m^3	Water abs. %
		f_{cu} MPa	Relative*	f_{st} MPa	Relative*	f_r MPa	relative*		
NC+NF	100	40.7	1.00	4.05	1.00	5.87	1.00	2362	2.26
NC+RF	90	36.2	0.89	3.49	0.86	5.13	0.87	2208	2.85
50LW+RF	110	32.8	0.81	3.12	0.77	4.16	0.71	1891	4.02
100LW+RF	130	24.5	0.60	2.27	0.56	3.03	0.52	1675	6.57
NC+NF+S	90	46.8	1.15	6.63	1.64	9.07	1.54	2392	1.78
NC+RF+S	70	42.0	1.03	5.78	1.43	8.05	1.37	2298	2.3
50LW+RF+S	95	39.0	0.96	5.32	1.31	7.13	1.21	1927	3.32
100LW+RF+S	105	29.6	0.73	4.02	0.99	5.32	0.91	1763	4.98

**Means relative to the control mix (NC+NF)*

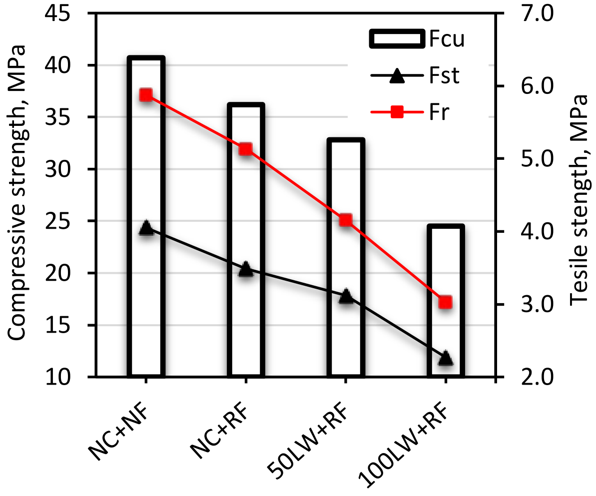

Fig. 1 Mechanical properties of the non-fibrous mixes

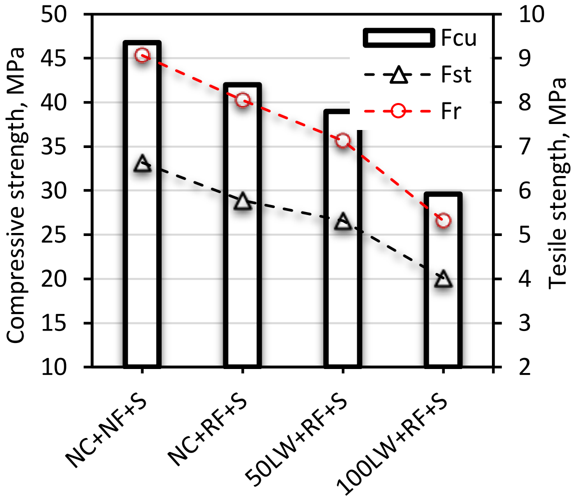

Fig. 2 Mechanical properties of the fibrous mixes

As seen in Figures 1 and 2, the substitution of 50% of gravel by LECA further reduced the compressive, splitting, and flexural strength of fibrous and non-fibrous concrete (by an average of 17, 22, and 25%, respectively), and the reduction was more obvious at 100% LECA (by 39, 42, and 45%, respectively). In lightweight concrete, aggregate, and not the interface between the aggregate and cement paste, determines the strength of the concrete because aggregate represents the frailest portion of the composite. In other words, being having inferior mechanical performance, LECA-based concrete exhibits a lower strength than normal weight concrete. Similar findings were also observed by [7]. As can be seen in Figure 3, the inclusion of hooked steel fibres improved all strengths, though the best improvement of up to 77% occurred in splitting tensile strength, followed by flexural strength (75%), and the lowest improvement of up to 21% was as expected achieved in compressive strength.

Table 6 shows the compressive strength of all mixes relative to that of the reference mix. The addition of steel fibre compensated for the adverse compressive strength due to the use of RF and 50% LECA. However, using steel fibres compensated for the adverseness of splitting tensile strength and flexural strength due to the use of RF, 50% LECA, and 100% LECA. Furthermore, apparently from Table 6, the splitting tensile strength of all fibrous concretes exceeds that of the reference mix (NC+NF) that was cast without fibre and without any recycled aggregate replacements. Similar behaviour occurred for flexural strength, except for the mix of 100% LECA (100LWA+RF+S), which showed a slightly lower value compared to the control mix. The achived enhancements in tensile strength caused by the incorporation of steel fibres were also previously reported by other researchers [17–18].

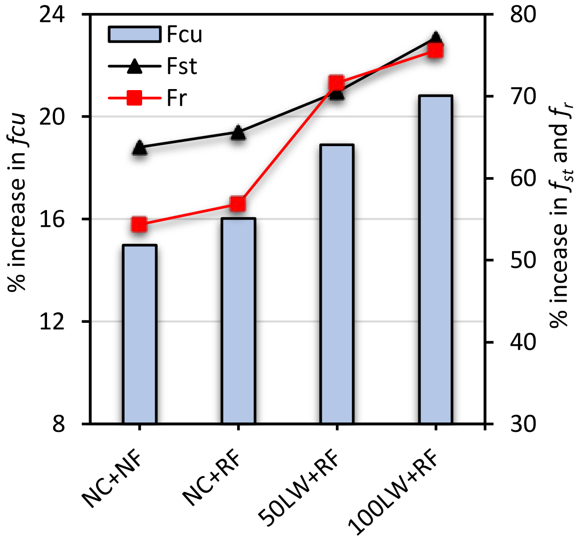

Fig. 3 Percentage increase due to SF addition

The ratios of splitting tensile strength and flexural strength to compressive strength are shown in Figures 4 and 5, respectively. Obviously, the highest ratios were recorded for reference mix followed by mixes with RF, and mixes with RF and 50% LECA, while mixes with 100% LECA exhibited the lowest ratios. The ratios of splitting and flexural strength to compressive strengths for non-fibrous concrete with LECA and RF were about 9.5% and 13.5%, respectively. The corresponding values for fibrous concretes were 13.5% and 18%, respectively.

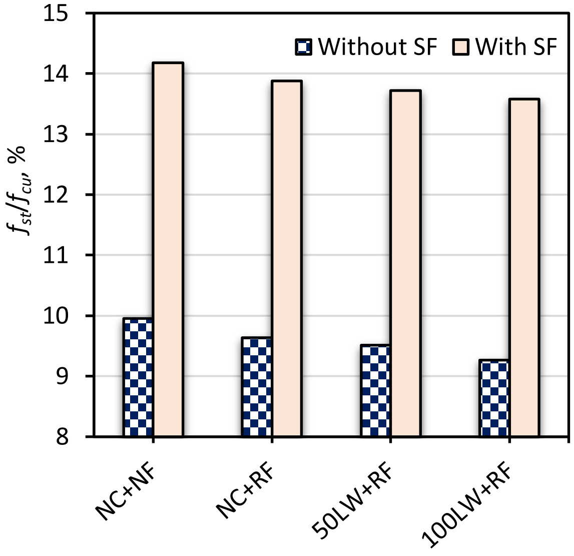

Fig. 4 f_{st} / f_{cu} ratio of the tested mixes

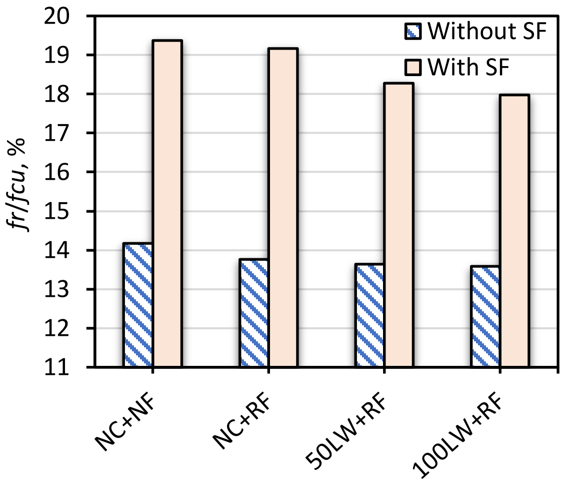

Fig. 5 f_r / f_{cu} ratio of the tested mixes

4.3 Dry Density and Water Absorption

It is clear from Table 6 that the use of RF reduced the dry density due to the porous nature of this type of aggregate, irrespective of whether the mix was reinforced with fibre or not, and the combination of RF and LECA further reduced the dry density. The dry density of concrete without SF, RF, and LECA was 2362 kg/ m^3, 2208 kg/m^3 for concrete with RF, 1891 kg/m^3 for concrete with RF and 50% LECA, and 1675 kg/m^3 for concrete with RF and 100% LECA. The dry density was higher for fibrous concrete specimens than non-fibrous ones due to the addition of high density steel fibres of 7800 kg/m^3. Nevertheless, the all produced fibrous LECA-based concrete mixes can be considered lightweight concrete as their densities were in the range of 1763 to 1927 kg/m^3.

As seen in Table 6, there was an increase in water absorption when RF was incorporated, and there was a further increase when LECA was used together with RF, though the water absorption of fibrous concrete was lower than that of non-fibrous concrete. Numerous variables, including the kind of aggregate, the kind of matrix, the w/c ratio, and the ITZ between the aggregate particles and paste, influence how much water concrete absorbs. In the current study, it appeared that the kind of aggregate and the characteristics of ITZ were crucial to the concrete's permeability. The derived concrete from LECA has a higher density because of its higher porosity compared to natural coarse aggregates. On the other hand, the porous ITZ due to the use of RF adversely affected the water absorption of the prepared concrete mixes [34].

4.4 Rebound Hammer and Ultrasonic Tests

The prepared concrete specimens were also assessed considering non-destructive tests through ultrasonic pulse velocity and rebound hammer, as seen in Figures 6 and 7. The findings of both non-destructive tests, apparently from Figures 8 and 9, are consistent with the mixes' strengths. In other words, the use of RF and/or RF+LECA reduced the rebound number (RN) and ultrasonic pulse velocity (UPV) for both fibrous and non-fibrous concrete, though the former performed better. The negative effects of recycled concrete aggregate on the nondestructive test results were also previously observed by other investigators but for normal-weight concrete [36].

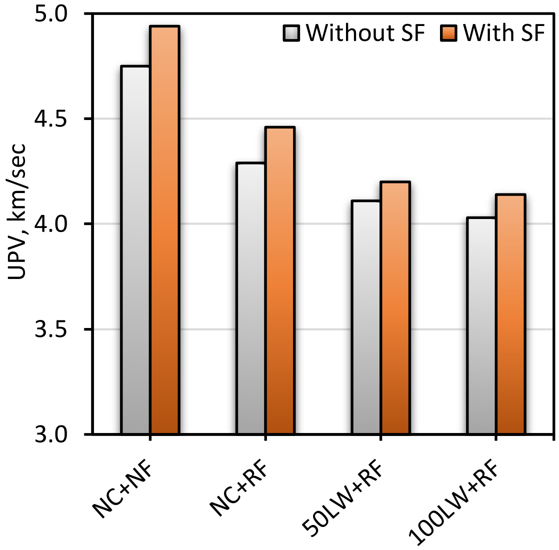

Fig. 14 UPV test results

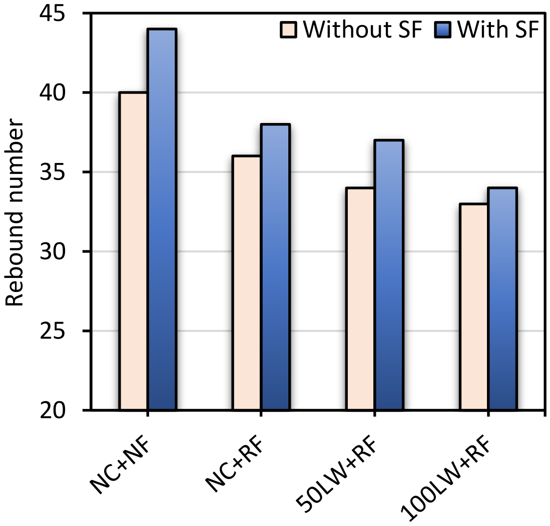

Fig. 15 Rebound number test results

Fig. 6 Ultrasonic pulse velocity (UPV) test

Fig. 7 Rebound hammer test

5. CONCLUSION

From the experimental investigation carried out in this study, it can be concluded that the use of recycled fine aggregate (RF) reduced the compressive strength, splitting tensile strength, and flexural strength of fibrous and non-fibrous concretes by an average of 10, 14, and 13%, respectively. The use of lightweight expanded clay (LECA) together with RF exhibited a further decrease in all strengths, and the mixtures in which full replacement of gravel with LECA showed the lowest performance compared with the other prepared mixes. Additionally, the rebound number and UPV findings were consistent with those of concrete strengths. On the other hand, the inclusion of hooked steel fibre compensated for the adverseness in strengths due to the use of RF and LECA, particularly the splitting tensile strength and flexural strength. The splitting tensile strength of all fibrous concrete exceeds that of the reference mix without fibres.

Similar behaviour almost occurred for flexural strength. The findings of this study also revealed that the dry density of concrete diminished when using RF in both fibrous and non-fibrous concretes. Further reductions occurred due to the use of both RF and LECA. When it came to water absorption, it was revealed that both fibrous and non-fibrous concretes absorbed more water when RF was added, and even more when LECA was used, though the fibrous concrete specimens exhibited lower water absorption than the non-fibrous ones. According to the promising mechanical properties of the lightweight LECA-based concrete, it is suggested to be used in reinforced concrete slabs and beams and other similar members so that the dead load on the foundations reduces as well as the total cost of the structure may be decreased.

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