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Prediction of Compressive Strength of Concrete incorporating fine recycled aggregate using regression analysis

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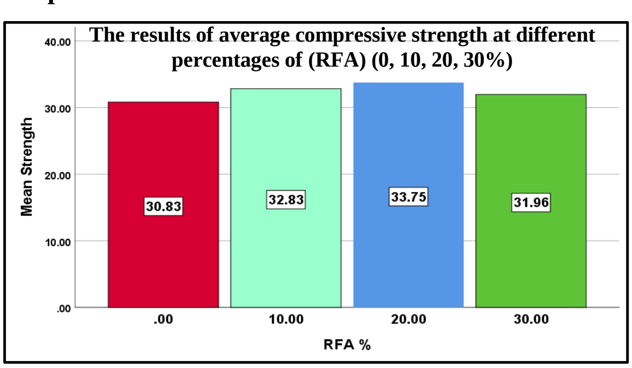
ABSTRACT

The practical use of recycled aggregate produced from crushing concrete waste in the production of new concrete reduces the consumption of natural aggregate and also reduces the amount of concrete waste that ends up in landfills. This study addresses the properties of concrete containing recycled fine aggregate (RFA) obtained from existing waste in Mosul. Four sets of concrete mixtures with different compressive strength (25, 30, 35 and 40MPa) were prepared, and for each strength, the effect of changing the replacement ratios of natural fine aggregate with recycled fine aggregate was studied, where four different ratios (0, 10, 20, 30) % of recycled fine aggregate (RFA) were adopted. The focus was on the compressive strength of concrete containing recycled fine aggregate due to the importance of this property as an indicator of concrete feature and the main determinant of its quality and the most important factor in design. The results showed a gradual decrease in the fresh properties of concrete containing recycled fine aggregate, such as slump and fresh density, as the proportion of recycled aggregate increased. However, there was an improvement in the compressive strength of the concrete mixes. Based on the practical results, equations were derived to predict the compressive strength of concrete containing recycled fine aggregate. According to the theoretical results obtained through analysis of variance (ANOVA), it was found that adding recycled fine aggregate at a rate of 20% is considered the best proportion, although the change in compressive strength is not significant.
Keywords: Recycled fine aggregate; Compressive strength; Slump; Analysis of variance.

Graphical abstract



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1. Introduction

About 10 billion tons of concrete are consumed annually, which means consuming one ton of concrete per person annually as a building material. Concrete is not considered environmentally applicable due to its negative effects on the environment. However, it remains one of the most common and widely used building materials [1]. Most of the world's infrastructure has been constructed using concrete. When concrete structures are demolished or renovated, concrete recycling is the common and increasingly used method to utilize the aggregate [2,3]. However, the process of concrete production requires the extraction of stones, either for cement production or for use as aggregate. Typically, fine aggregate for concrete is obtained by extracting sand from river beds or sea coasts, but these activities cause serious environmental problems, Altering the water flow in rivers or currents in seas leads to coastal erosion, negatively affecting nearby infrastructure[4].The use of recycled aggregate contributes to promoting the recycling of concrete waste in the construction industry, in addition to preserving natural and environmental resources. Research has mostly focused on the treatment of concrete waste, its gradation, mechanical properties, and durability aspects [5,6]. Despite this, previous studies have not indicated that the use of recycled aggregate in structural concrete is inappropriate. Recent research conducted on concrete containing fine recycled concrete aggregate [7-14] has shown that there is a positive role for recycled aggregate in structural concrete, based on the results of tests and analysis in these studies, the following conclusions can be drawn:

- Recycled fine aggregate improves the properties of hardened concrete up to an optimal replacement ratio of 25%. Beyond this value, the concrete strength deteriorates.
- The results show that concrete containing crushed sand requires the addition of superplasticizers to achieve the same workability as the reference concrete containing natural fine aggregate. It also exhibits higher strength compared to the reference concrete.
- The use of recycled fine concrete aggregate does not harm the mechanical properties of concrete, especially at replacement ratios up to 30%.
- Results indicate that the properties of self-compacting concrete made from river sand and recycled fine aggregate showed only slight differences. The effectiveness of using recycled fine and coarse aggregate along with rejected fly ash and Class F fly ash in self-compacting concrete has been proven.
- Replacing natural aggregate with recycled aggregate affected the compressive strength and modulus of elasticity of the concrete. In general, concrete made using recycled aggregate showed lower compressive strength. However, there was an increase in compressive strength for concrete made with recycled fine aggregate from ceramic bricks (RFB).

Although the use of recycled fine aggregate in concrete tends to be associated with negative effects on its compressive strength, the researcher (Leite) in 2001 [15] noted that its use in structural concrete is feasible. Ismail et al. [16] studied the effect of replacing recycled fine aggregate from old concrete with natural fine aggregate to produce high-strength cement mortar. The results of the study indicated that replacing (25%) of recycled fine aggregate with natural fine aggregate did not lead to a significant reduction in compressive strength but contributed to an increase of approximately (7%) and (6%) compared to the reference mix for test ages of 28 and 56 days, respectively. In 2007, L. Evangelista and J. de Brito [9] conducted a study on the use of recycled fine aggregate from concrete as a partial or total alternative to natural fine aggregate (sand) in the production of structural concrete. The researchers concluded that recycled fine aggregate can be used as a partial substitute for natural aggregate in structural concrete at ratios of up to (30%) without negatively affecting the mechanical properties of concrete. On the contrary, other research concluded that recycled fine aggregate reduces compressive strength [17-20], while some mentioned that it has no effect [21]. The compressive strength of concrete is generally considered one of its most important properties, although in many practical cases, other characteristics such as durability and permeability may be more important in reality. However, the compressive strength of concrete gives a clear picture of the quality and type of concrete, as compressive strength is directly related to the structure of the hardened cement paste. Moreover, this property is considered a fundamental element in structural design [22].

2. Research Objective

After looking at a number of studies, it became apparent that there are contradictions in the conclusions. Some research reported that adding recycle fine aggregate reduces compressive strength, while other studies mentioned that it enhances it, and some found no effect. Therefore, the motivation for conducting the current study was to determine the impact of recycled fine aggregate on the compressive strength of concrete. This serves as an attempt to enhance the existing results in this field and to provide a clearer picture. The research also aims to propose equations through which the compressive strength can be predicted at different ages and for different levels of compressive strength of concrete containing recycled fine aggregate in various proportions. Additionally, equations have been proposed that can predict the compressive strength at 28 and 56 days based on the components of the concrete mix.

3. Experimental Program

3.1. Materials

3.1.1. Cement

For preparing the concrete mixes, ordinary Portland cement complying with the Iraqi Standard Specification (IQS 5:2016) [23] was adopted. tables (1) and (2) show the chemical compounds and physical properties of the cement used, respectively.

Table 1. Chemical Composition of the Cement.

Chemical Composition	Value %	Limits Iraqi Standard (No.5, 2016)	Chemical Composition	Value %
SiO_2	21.4	----	C_3S	45.8
Al_2O_3	4.16	----	C_2S	26.57
Fe_2O_3	3.13	----	C_3A	5.73
CaO	59.81	----	CAF	9.53
MgO	2.27	≤ 5	L.S.F	88.39
SO_3	0.89	≤ 2.8	Solid Solution	14.08
Free Lime	2.56	----		
Loss on ignition	0.19	≤ 4		
Insoluble residue	0.7	≤ 1.5		

Table 2. Physical properties of the cement.

Physical properties	Test results	Limits Iraqi Standard (No.5, 2016)
Initial setting time (min)	135	≥ 45 min
Final setting time (hr)	4:00	≤ 10 hr
Fineness sieves no. 170 (90 µm)	4.6 %	≤ 10 %
Compressive strength 3 days (MPa)	19.87	≥ 15
7 days (MPa)	27	≥ 23

3.1.2. Fine Aggregate

Local river sand (Natural Fine Aggregate) was used. After conducting sieve analysis, it was found to comply with the American specification ASTM C33 [24]. Recycled Fine Aggregate (RFA) was also used, which is the aggregate produced from the debris resulting from the demolition of concrete buildings due to the war in Mosul city. These concrete remains were collected and transported to the Al-Adhba area, where there is a recycling center, as shown in Fig. 1. Two types of recycled aggregate are produced in different sizes (fine and coarse). The recycled aggregate used in the study is recycled fine aggregate with sizes (0-5) mm. tables (3) and (4) show the sieve analysis and physical properties [25] of natural fine aggregate and recycled fine aggregate, respectively.

Fig 1. Recycled Fine Aggregate.

Table 3. Sieve analysis.

Sieve size (in)	% Passing (NFA)	% Passing (RFA)	ASTM C33
No.4	100	100	95-100
No.8	81.1	80.6	80-100
No.16	60.2	57.5	50-85
No.30	44.6	40.3	25-60
No.50	25	22	5-30
No.100	5	8.2	0-10

Table 4. Physical properties.

Physical properties	NFA	RFA
Apparent specific gravity	2.72	2.67
Absorption capacity %	1.8	8.3
Fineness modulus	2.8	2.9
Unit weight kg/m³	1798	1481

3.1.3 Natural Coarse Aggregate (Coarse Aggregate)

Rounded river gravel (Natural Coarse Aggregate) with a maximum size of (19 mm) was used as coarse aggregate in all concrete mixtures. Tables (5) and (6) show the sieve analysis [23] and physical properties[26] , respectively, of the coarse aggregate used in the current study.

Table 5. Sieve analysis.

Sieve size (in)	% Passing	ASTM C33
1	100	100
3/4	100	90-100
3/8	40	20-55
No.4	0	0-10

Table 6. Physical properties.

Apparent specific gravity	2.74
Absorption capacity %	0.43
Unit weight kg/m³	1728

3.2. Concrete Mix Proportion *and Tests*

As previously mentioned, the main objective of this study is to determine the effect of adding recycled fine aggregate on the compressive strength of concrete. To conduct this investigation, four groups of concrete Mixtures with different compressive strengths (25, 30, 35, 40 MPa) were prepared. The concrete Mixtures were designed according to ACI 211.1-91[27]. In each concrete mix, the natural fine aggregate was replaced by volume with four different percentages of recycled fine aggregate (0, 10, 20, 30%) as a substitute for natural fine aggregate. It is worth noting that when preparing the mixtures, the amount of water required by the recycled fine aggregate was calculated and added to the concrete mix water to change its state to Saturated Surface-Dry (SSD) condition so as not to affect the effective water-to-cement ratio (effective w/c). Table 7 shows the details of the concrete Mixtures. To evaluate the behavior of concrete containing recycled fine aggregate, the following tests were conducted slump test in accordance with ASTM C 143[28], fresh density measurement and compressive strength test on concrete cubes (150×150×150 mm) at different ages (3, 7, 28,56 days).

Table 7.Mix Proportion of Concrete Mixtures (kg/m^3).

Mix	% FRA	Cement	Natural fine aggregate	Fine recycle aggregate	coarse aggregate	Water
M25	0	302	789	0	1071	174
	10	302	724	65	1071	174
	20	302	659	130	1071	174
	30	302	594	195	1071	174
M30	0	364	738	0	1071	177
	10	364	677	61	1071	177
	20	364	616	122	1071	177
	30	364	555	183	1071	177
M35	0	400	708	0	1071	184
	10	400	650	58	1071	184
	20	400	592	116	1071	184
	30	400	534	174	1071	184
M40	0	440	675	0	1071	182
	10	440	619	56	1071	182
	20	440	563	112	1071	182
	30	440	507	168	1071	182

4. Results and Discussion

4.1. Fresh Properties

4.1.1. Slump

Fig. 2. illustrates the relationship between concrete mixtures and slump for all replacement ratios of recycled fine aggregate. This figure clearly shows that the concrete slump is affected by the presence of recycled fine aggregate.

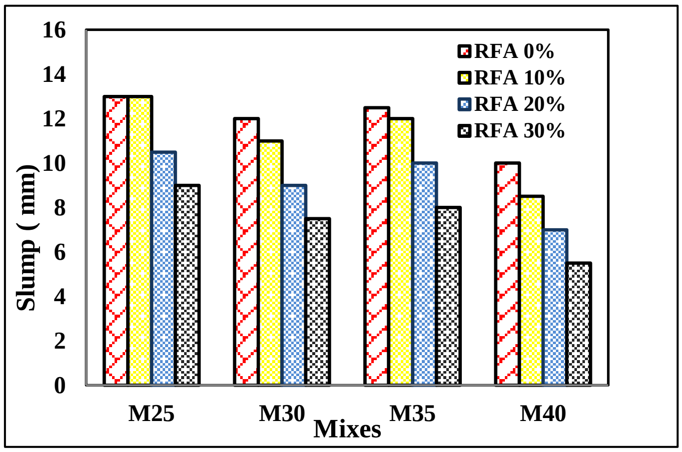

Fig 2. Effect of FRA on slump of concrete.

It is evident that the recycled fine aggregate had a negative impact on the workability of concrete. Note that when preparing the mixes, the amount of water needed by the recycled fine aggregate was calculated and added to the concrete mix water so as not to affect the effective w/c ratio. However, despite this, the workability decreased significantly [29]. The decrease in slump increased with the increase in the replacement ratio for all concrete mixtures. This is due to the angular shape and rough texture of the recycled aggregate used in the study, which leads to increased interlocking and friction, reducing movement between particles and consequently reducing workability [16] [30-32].

4.1.2. Fresh Density

Fig. 3. shows the relationship between concrete mixtures and fresh density for all replacement ratios of recycled fine aggregate.

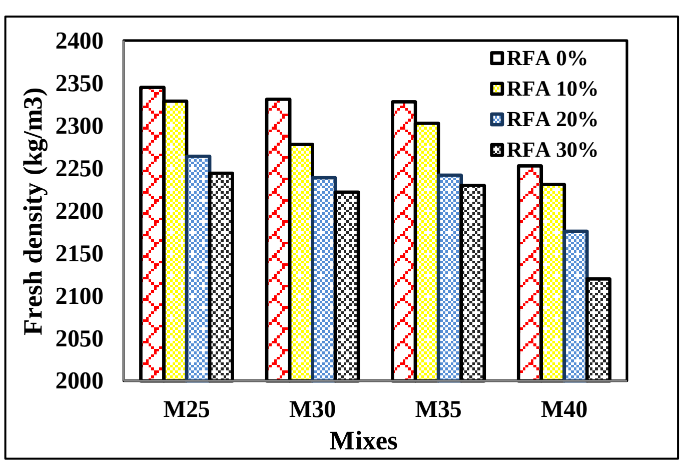

Fig 3. Effect of FRA on fresh density.

As shown in the figure, the fresh density of concrete decreases with the presence of recycled fine aggregate. The percentage decreases in fresh density are (0, 0.68, 3.45, 4.3) % compared to the reference mixture for M25 (0, 2.27, 3.9, 4.7) % compared to the reference mixture for M30 (0, 1.07, 3.69, 4.2) % compared to the reference mixture for M35 while the decrease percentages reached (0, 0.98, 3.41, 5.9) % compared to the reference mixture for M40. This decrease in density is attributed to several reasons, including the presence of less dense residual cement mortar adhering to RFA particles. Another reason contributing to the decrease in fresh density is that the unit weight of recycled fine aggregate is less than that of natural fine aggregate. Furthermore, the specific gravity of recycled fine aggregate is lower than that of natural fine aggregate [30] [33].

4.2 Properties of Hardened Concrete

4.2.1 Compressive Strength

Fig 4. illustrates the development of compressive strength with age for concrete containing recycled fine aggregate at ages (3,7,28,56) days, for compressive strengths of (25 MPa), (30 MPa), (35 MPa), and (40 MPa), with replacement ratios of (0, 10, 20, 30) % for each strength level.

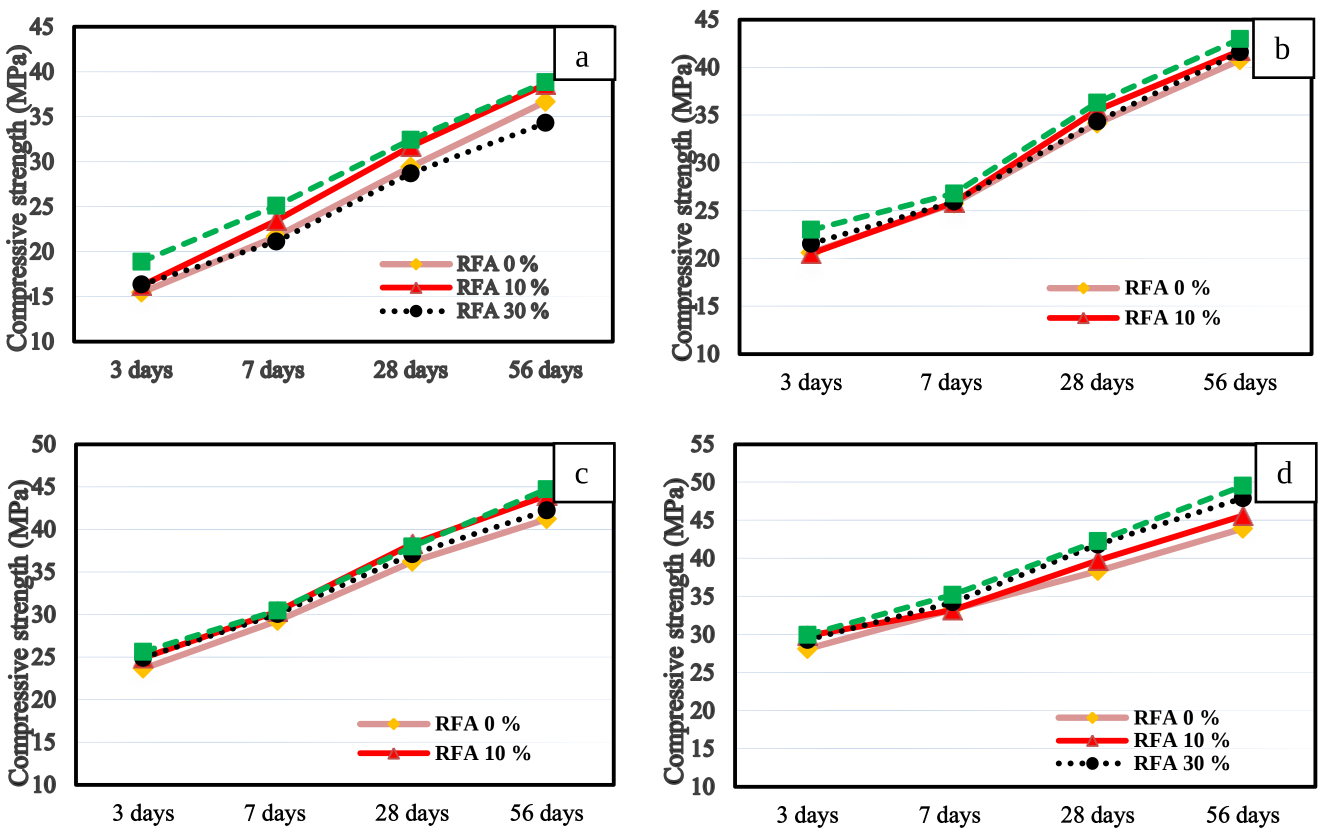

Fig. 4. Compressive Strength vs Age (a) M25; (b) M30; (c) M35; (d) M40.

The results show that the compressive strength of concrete containing recycled fine aggregate increases with increasing recycled aggregate up to a replacement ratio of (20%) [9] [10]. A slight decrease in compressive strength is observed when the aggregate ratio increases to (30%). The increase in compressive strength is due to the presence of additional cement associated with the recycled fine aggregate, which can reach up to (25%) of the recycled aggregate [33]. Another possible reason is the internal curing effect of FRA, whereby water initially absorbed into the pores becomes available at later stages for cement hydration. Also, the rough texture and angular shape due to grinding and crushing may increase the friction resistance of the aggregate, leading to increased concrete strength, which heavily depends on aggregate strength [8]. One reason for increased strength is the source of the recycled aggregate being high-strength concrete [34]. However, adding more recycled fine aggregate to replace natural fine aggregate, which is more porous due to the presence of old adhered mortar, leads to more voids and pores in the concrete, ultimately reducing strength [19], as observed in this study. Using the statistical analysis program (SPSS) and through multiple linear regression analysis, relationships were developed linking the replacement ratios of recycled fine aggregate with the compressive strength of concrete mixtures over time, as shown in Fig. 5. These relationships were used to derive equations that can predict the compressive strength at any age, with a maximum of 56 days, and at recycled fine aggregate addition rates ranging between 0-30%. Four equations were derived, each specific to a particular concrete mix: the first equation is for the (M25) mix, the second for the (M30) mix, the third for the (M35) mix, and the fourth for the (M40) mix, as shown below.

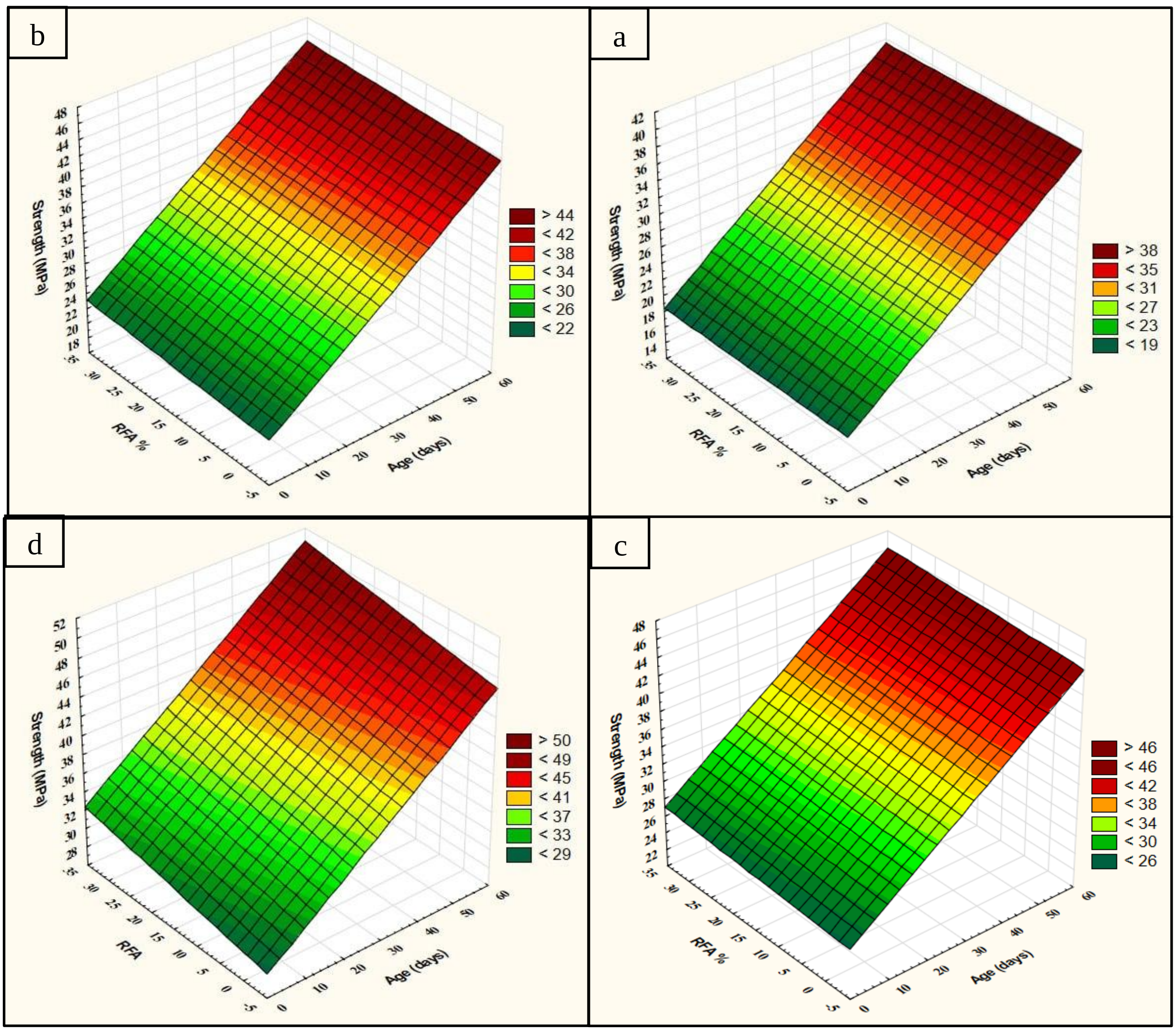

Fig 5. Effect of FRA vs Age on Compressive Strength (a) M25; (b) M30; (c) M35; (d) M40.

$f_{cu} = 18.63 + 0.353\ D - 0.008\ RFA$ (1

$f_{cu} = 22.05 + 0.365\ D + 0.03\ RFA$ (2

$f_{cu} = 25.85 + 0.318\ D + 0.032\ RFA$ (3

$f_{cu} = 29.05 + 0.306\ D + 0.094\ RFA$ (4

Where:
f_{cu} (MPa)**:** Compressive strength of the cube.
D: Age (Days).
RFA: Percentage replacement ratio of recycled fine aggregate
Table (8) presents the results of multiple linear regression analysis for the impact of both recycled fine aggregate and age (in days) on compressive strength, as represented by the statistical parameters of the above equations, along with the coefficient of determination (R^2), which serves as an indicator of the quality and suitability of the equation for each compressive strength. The linear equation consists of three variables, one of which is the dependent variable, compressive strength, while recycled fine aggregate and age (days) are independent variables that affect compressive strength.

Table 8. Results of the effect of both (FRA) and age on compressive strength

Regression analysis					
Mix	**Model**	**Coefficient B**	**R^2**	**p-value**	**t_{cal}**
M25	Constant	18.635	0.875	0	22.146
	Age (days)	0.353		0	17.736
	RFA (%)	-0.008		0.838	-0.205
M30	Constant	22.050	0.930	0	34.939
	Age (days)	0.365		0	24.451
	RFA (%)	0.03		0.284	1.083
M35	Constant	25.845	0.892	0	36.874
	Age (days)	0.318		0	19.227
	RFA (%)	0.032		0.307	1.033
M40	Constant	29.047	0.917	0	49.478
	Age (days)	0.306		0	22.027
	RFA (%)	0.094		0.001	3.611

tabular value (t_{Tab} = 1.96).

The results of the stepwise regression analysis shown in the table above indicate the following:

The effect of age on compressive strength was significant, as the (P-Value) was less than (0.05) and the calculated value (t_{Cal}) was greater than the tabular value of (1.96). The effect of recycled fine aggregate on compressive strength was significant only for the compressive strength of (M40), as the (p-value) was less than (0.05) and the calculated value (t_{Cal}) was greater than the tabular value of (1.96). This effect is attributed to the increase in cement content, in addition to the unhydrated cement in the recycled fine aggregate [33].

The robust least squares method was used to derive a general equation that allows the prediction of the compressive strength of concrete containing recycled fine aggregate (RFA) at ages of (28) and (56) days, as shown in equations (5) and (6) respectively. This was done at replacement ratios between (0-30%) and cement content ranging between (302-440 kg/m³). This equation was based on the experimental data presented in the equations below.

$$f_{cu}\,(MPa) = -115.86 + 0.172\,C + 0.8377\,RFA + 0.133\,S - 0.0571\,W \quad (5$$

$$f_{cu}\,(MPa) = -192.9 + 0.254\,C + 1.48\,RFA + 0.237\,S - 0.19\,W \quad (6$$

Table (9) presents the results of the statistical analysis of the effect of concrete mixture components on compressive strength, as represented by the statistical parameters of the general equation at ages of (28) and (56) days. In this general equation, compressive strength is considered the dependent variable, while concrete components such as cement, water, recycled fine aggregate, and sand represent the independent variables.

Table 9. Results of the analysis of the effect of concrete mix components on compressive strength.

Regression analysis				
	Independent variable	Coefficient B	R^2	P-Value
The General Equation at (28 days)	Constant	-115.86	0.71	0.0714
	Cement	0.172		0.0003
	WATER	- 0.0571		0.6511
	RFA	0.8377		0.0267
	Sand	0.133		0.0347
The General Equation at (56 days)	Constant	-192.9	0.73	0.0038
	Cement	0.254		0.0000
	WATER	-0.19		0.1461
	RFA	1.48		0.0002
	Sand	0.237		0.0003

According to the results presented in the table above, it is evident that the effect of concrete components on compressive strength, including cement, recycled fine aggregate, and sand, is significant with a p-value smaller than (0.05). In contrast, the effect of water is not significant with a p-value larger than (0.05). The value of the coefficient of determination (R^2) for the two equations indicates that the concrete components explain approximately (71.73%) of the variations in compressive strength.

Based on the Fig 6. below, it is evident that the model linking the independent variables and the dependent variable is a good model, as the actual values indicated in (red) are close to the estimated values indicated in (green). Additionally, the majority of the error values indicated in (blue) fall within the range of (-2 to +2), which is an indication that the error variable follows a normal probability distribution.

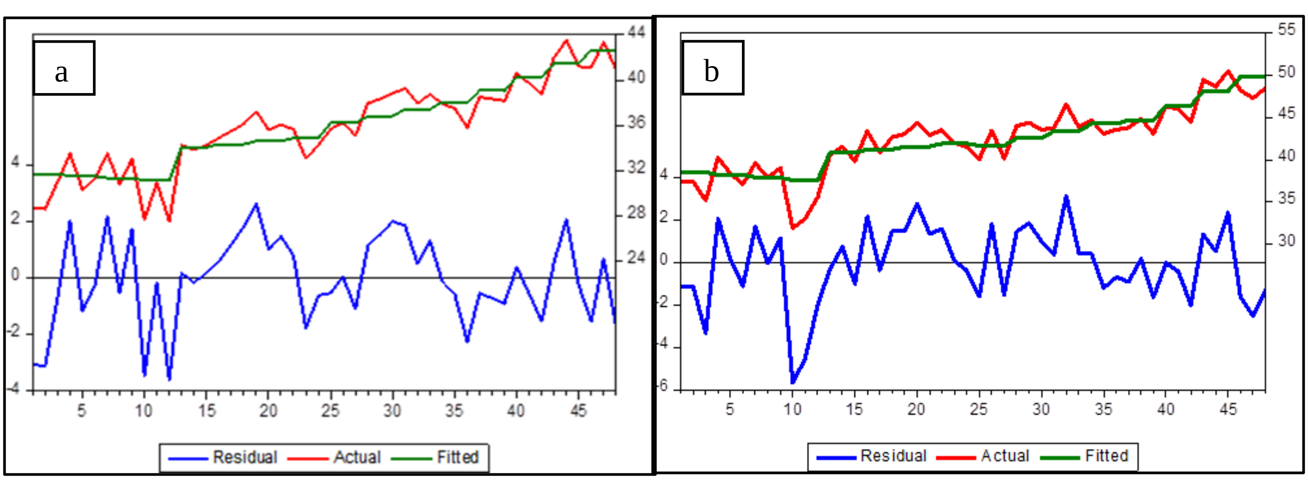

Fig. 6. Illustrates the relationship between the actual and estimated values of compressive strength at (a) 28 days; (b) 56 days.

In this study, the concrete mixtures were evaluated using the (Duncan) test at a significance level of (0.05). According to the results of this test, it was found that there are no statistically significant differences between the average strength at the different percentages of recycled fine aggregate added to the concrete mixture. This is indicated by the p-value of (0.125), which is greater than (0.05). Nevertheless, it was observed that the ratio of (20%) is considered the best ratio compared to the reference ratio of (0%), as shown in Table (10) and Fig. 7, respectively.

Table 10. Shows the results of the Duncan test.

Compressive Strength			
	RFA %	N	alpha = 0.05
			1
Duncan[a]	.00	48	30.83
	10.00	48	32.83
	20.00	48	33.75
	30.00	48	31.96
	P-Value		.125

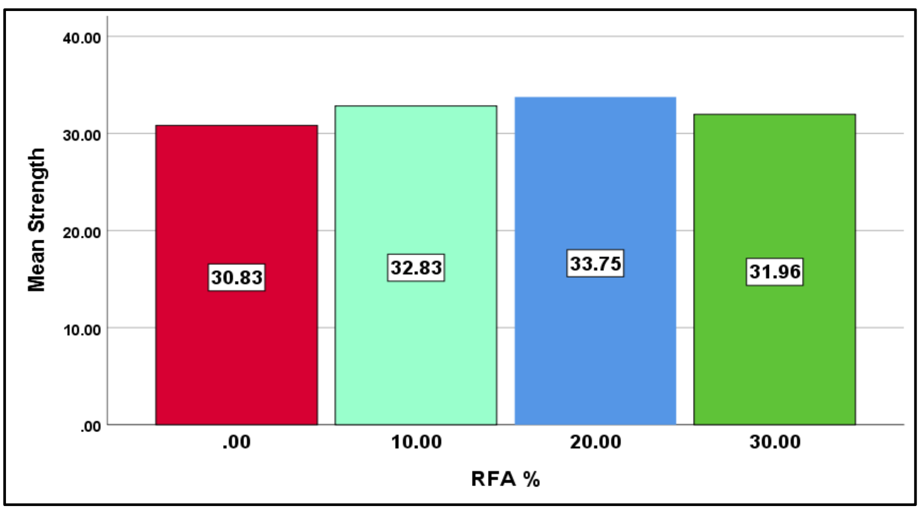

Fig. 8. Shows the results of average compressive strength at different percentages of (RFA) (0, 10, 20, 30%)

5. Conclusion

Based on the results obtained, the conclusions can be summarized as follows:

- The workability decreased significantly, although when preparing the mixes, the amount of water required by the recycled fine aggregate was calculated and added to the concrete mix water so as not to affect the effective w/c ratio.
- The density of fresh concrete decreased with the presence of recycled fine aggregate, and the percentage reductions in fresh density were (0, 0.68, 3.45, 4.3%) compared to the reference mix for M25 strength, the reduction percentages decreased to (0, 2.27, 3.94, 4.67%) compared to the reference mix for M30 compressive strength, and the reduction percentages reached (0, 1.07, 3.69, 4.2%) compared to the reference mix for M35 strength, while the reduction percentages reached (0, 0.98, 3.41, 5.9%) compared to the reference mix for M40 compressive strength.

- The results show that adding recycled fine aggregate has an effect on improving the compressive strength of concrete. The increase in compressive strength was observed up to an addition rate of (20%). Then, by increasing the fine aggregate content to (30%), the compressive strength decreased, but only slightly. The percentage increase in compressive strength at 28 days for the mixture (M25) at rates of (10, 20, 30%) was (7.75, 10.26, -2.45%) respectively, compared to the reference mixture. The percentage increases for mixture (M30) were (4.07, 6.39, 0.58%) compared to the reference mixture. The percentage increases for mixture (M35) were (5.8, 4.86, 2.43%) compared to the reference mixture, while the percentage increases for mixture (M40) reached (3.53, 10.23, 9.0%) compared to the reference mixture.
- Using a statistical analysis program and through multiple linear regression analysis, equations have been proposed to predict compressive strength at any age between (3-56) days and at recycled fine aggregate percentages between (0-30%). For example, with an age of 14 days and a recycled fine aggregate percentage of 10%, the proposed equations can be used to predict compressive strength.
- Using the statistical program, a equation was formed to predict the compressive strength at ages of (28,56) days for concrete containing recycled fine aggregate based on the concrete mix components.
- According to the (Duncan) test, there were no statistically significant differences between the recycled fine aggregate replacement ratios, although it was noted that the (20%) ratio is considered the best.
- The study demonstrated the feasibility of incorporating construction and demolition waste into new concrete production using recycled fine aggregate. The results confirmed that adding up to 30% of recycled fine aggregate does not negatively affect the properties of concrete but actually enhances its performance, which is consistent with previous studies. In addition to improving concrete properties, the use of recycled aggregate helps reduces the consumption of natural resources and protects the environment by decreasing construction and demolition waste. Although recycled fine aggregate has a negative impact on workability, the concrete mixes remained within acceptable slump limits, and this issue can be mitigated by using plasticizers to improve workability.

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