Combined Influence of Fly Ash and Recycled Coarse Aggregates on Strength and Economic Performance of Concrete

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Abstract

Recycled coarse aggregates (RCA) and fly ash (FA) are materials with least to very low global warming potential. Considering long term strength and durability, various studies have suggested to use RCA in concrete with FA. This research paper deals with the strength and economic performance of concrete made with individual and combined incorporation of FA and RCA. Nine different mixtures of concrete were prepared by varying the incorporation levels of RCA and FA. 0% RCA, 50% RCA and 100% RCA were used in concrete with three different levels of FA (0%FA, 20%FA, and 40%FA). The compressive strength of each mixture of concrete was determined at the age of 3, 28, 90 and 180 days. To evaluate economic performance cost of 1 m^3 of each mixture of concrete was compared to that of the control mixture having 0% RCA and 0% FA. Results showed that RCA was detrimental to the compressive strength of concrete at all ages, whereas, FA reduced early strength but improved the strength at later ages of testing i.e. 90 and 180 days. FA plus RCA mixes also showed lower early age strength but gained higher strength than conventional concrete at the age of 180 days. RCA did not reduce the cost of concrete effectively. FA despite having a very high transportation cost, it reduced the cost of concrete efficiently. FA did not only reduce the cost of binder but also lower the demand of plasticizer by improving workability. Cost to strength ratio (CSR) analysis also indicated that FA significantly improve the combined economic and strength performance of RCA concrete mixes.

Keywords: Recycled Aggregate Concrete; Recycled Aggregates; Fly Ash; Compressive Strength; Economic Performance.

1. Introduction

Concrete is used more than any other manmade material in the world due to its unique advantages. Formability, higher strength and durability, and the cost-effectiveness of OPC concrete makes it more adaptable material than other conventional materials such as wood, steel, bricks, stones, etc. But it possesses a very high global warming potential associated with its vital components such as OPC and NCA.

In construction industry necessity for sustainability is obvious. Not only construction industry should lessen its carbon footprint, but it should also contribute to preserve the natural resources which are vital for continuous growth and long-term economy. Therefore, waste materials are undergoing extensive research worldwide so that they can be replaced with the conventional materials in order to lessen the impact of the construction industry on environment, society and economy. The requirement of NCA to produce the concrete will reach to about 40 billion tons/annum with coming 20 years [1, 2]. On the other hand, construction and demolition activities generate 90 million tons of waste in major countries around the world i.e. Japan, Europe and USA [3]. In this scenario, best practice would be to streamline C&DW into the concrete industry by manufacturing recycled aggregates. On the other hand, total world production of Portland cement

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has reached up to a level of 4200 million tons per annum [4]. Cement industry consumes massive amount of fuels and also natural resources of limestone, clay, etc., in order to meet the requirements of energy and raw materials. It was estimated that the cement industry alone shares about 7% to the total greenhouse gas emissions [2, 5]. By reducing the demand of OPC in construction sector, its negative impact on the environment can be reduced. A possible way will be to use supplementary cementitious material with lower carbon emissions associated with its manufacturing. FA is produced as a by-product of coal electricity power plants. Handling and disposal of FA has become a major concern as worldwide consumption of 3500 million tons of coal produces a huge portion of waste as FA [6]. So, replacement of any part of OPC in concrete with cementitious waste material like FA can bring a huge deal of economy and sustainability to concrete. Not only this practice will help concrete in lowering its carbon footprint, but it may save us from troubles of waste management pertaining to FA.

Researchers have reported that using recycled aggregates as partial or full replacement of natural aggregates can help in reducing the carbon footprint of concrete but some properties like workability, strength, and durability are badly affected [7-10]. Whereas, partial replacement of OPC with a pozzolanic binder like FA reduce carbon emissions associated with concrete manufacturing effectively with some loss in strength and durability at early ages [11-14]. Replacing waste materials with conventional construction materials not only minimize the negative environmental impact of concrete but also help in preserving raw materials for future usage.

Recycled aggregates are usually obtained from construction and demolition wastes (C&DW). Recycled aggregates from C&DW are of various types i.e. recycled concrete aggregates, recycled mortar aggregates, recycled brick aggregates or sometimes their different combinations are referred to mixed recycled aggregates (MRA). Out of these, recycled concrete aggregates are useful for superior concrete works i.e. reinforced, precast and prestressed concrete. Recycled aggregates have very high roughness and water absorption than natural aggregates which in turn increase the harshness of fresh concrete, therefore, RCA concrete mixtures are less workable and require higher water demands than their conventional counterpart [10, 15]. Due to presence of adhered mortar in RCA, strength and durability properties of concrete are affected badly [14, 16]. FA has positive impact on workability, durability and later strength of concrete than RCA. By virtue of the relatively inert nature of glassy beads of FA, durability of concrete under aggressive conditions is improved. FA particles react with unused calcium hydroxide $(Ca(OH)_2)$ produced in the hydration of cement. Products of this reaction increase the durable calcium silicate hydrates (CSH-gel) content in the binder matrix of concrete.

The economic impact of combined use of RCA and FA in concrete is still not yet studied broadly. Concrete with RCA has been proved weaker and expensive product than conventional concrete in a study which investigates the financial assessment of RCA in concrete [17]. The lower strength of RCA can increase the CSR of concrete. Studies have shown that using recycled aggregates in construction industry as replacement of conventional aggregates is an economical and eco-efficient practice than disposing off construction and demolition waste in landfills and backfilling [18-21].

Various studies have investigated the effect of individual and simultaneous incorporation of RCA and FA on fresh and hardened properties of concrete [16, 22-27]. To the best knowledge of authors combined use of RCA and FA in concrete has not been investigated viewing both economic and strength performance of concrete. Sustainability in the construction industry is inevitable but utilization of both RCA and FA in concrete must also be investigated considering both economy and strength i.e. using cost to strength ratio (CSR) analysis. RCA and its conventional counterpart NCA both involve same manufacturing process, so that influence of RCA on the cost of concrete may become insignificant. Moreover, longer transportation distances associated with FA may increase its final cost at the hand of consumer. So, considering these shortcomings of RCA and FA, a CSR analysis may provide a useful tool in order to optimize potential waste materials in concrete.

2. Materials and Methods

2.1. Materials

In this experimental study, general purpose Portland cement of Grade 43 (Fauji Cement) was used. Properties of cement conform to specifications of general-purpose OPC given under ASTM C150 [28] and are shown in Table 1. Low calcium type of FA was used as a pozzolanic binder. FA was obtained from Port Qasim power plant in Karachi. Results of chemical and particle analysis of FA are shown in Table 2. According to ASTM C618 [29] specifications of this FA conform to Class F.

Natural river sand of Lawrance Pur brand was used as fine aggregate in all concrete mixes throughout the experimental study. The crush stone of Margalla brand was used as a natural coarse aggregate (NCA). General properties of both coarse and fine aggregates are given in Table 3. RCA was obtained through the manual crushing of tested specimens of concrete. Specimens crushed to make RCA, had compressive strength value in the range of 30-35 MPa. After manual crushing aggregates were sieved and separated according to sizes of NCA. Maximum size of coarse aggregates was maintained as 22.5 mm for both NCA and RCA, whereas minimum size for both was retain of 4.75 mm

sieve. General properties of RCA are also given in Table 3. All aggregates used in this experimental study adhere to ASTM specifications of aggregates for concrete [30]. Gradation curves of all aggregates are shown in Figure 1.

Tap water free from organic impurities was used in the mixing of concrete. Anticipating the workability loss at the inclusion of RCA in concrete mixtures, a high range plasticizer (Sikament 520) was used. Plasticizer's properties conform to Type F of admixtures according to ASTM C494 [31] specifications. Overview of materials in this experimental study is shown in Figure 2.

Table 1. General properties of OPC provided by the supplier

Chemical characteristics	Result	Physical characteristics	Result
SiO_2	22.5%	Specific gravity	3.14
Al_2O_3	5%	Specific surface (m^2/kg)	322
Fe_2O_3	4.0%	Consistency	29.25%
CaO	64.25%	Initial setting time	1hr, 53 min
MgO	2.5%	Final setting time	3 hr, 58 min
SO_3	2.9%	Soundness	0.102%
Na_2O	0.2%	28 days compressive strength	41.56 MPa
K_2O	1%	-	-
Loss on ignition	0.64%	-	-

Table 2. General properties of FA provided by the supplier

Chemical characteristics	Result	Physical characteristics	Result
SiO_2	57%-65%	Specific gravity	2.34
Al_2O_3	28%-32%	Specific surface (m^2/kg)	423
Fe_2O_3	1%-4%	Consistency	32.5%
CaO	1%-2%	Initial setting time	-
MgO	0.5%	Final setting time	-
SO_3	1.09%	Soundness	0.034%
Na_2O	1.5% Maximum	Passing through a 40-micron sieve	94%
Lime reactivity	5.8%	-	-
Loss on ignition at 950ºC	9.04%	-	-

Table 3. General properties of aggregates

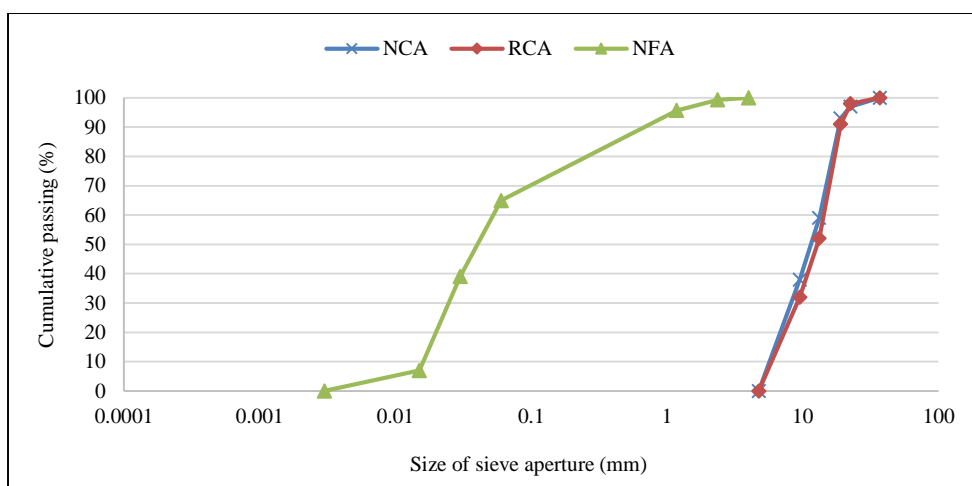| Property	NFA	NCA	RCA
Max. nominal size (mm)	4.00	22.50	22.50
Min. nominal size (mm)	0.075	4.75	4.75
Saturated surface dry water absorption (%)	1.40	1.08	7.22
10% fine value (kN)	-	157	125
Bulk density (kg/m^3)	1614	1534	1395
Abrasion value (%)	-	29.42	41.23

Figure 1. Gradation of aggregates

Figure 2. Overview of materials (a) RCA, (b) NCA, (c) Fine aggregate, (d) OPC, and (e) FA

2.2. Composition of Concrete Mixtures

Three series of concrete mixes were produced by using three different levels of RCA (0%RCA, 50%RCA, and 100%RCA) as coarse aggregates. In each of these three series, three different levels of FA (0%FA, 20%FA, and 40%FA) were incorporated as partial replacement of OPC (by weight). In this study, incorporation level of FA was not increased beyond 40% because after consumption of excess $Ca(OH)_2$ (which is produced in the hydration of cement) in the binder matrix of concrete, FA particles may behave as mineral filler rather than binder [32]. Also increasing the level of FA may also cause significant reductions in early age strength due to slow nature of pozzolanic reaction between aluminosilicate particles of FA and $Ca(OH)_2$. Details of the composition of each mixture are given in Table 4. C1 serves as a conventional/control mix having 0%FA and 0%RCA. Water to cement ratio was maintained as 0.50 through all of the concrete mixes. Water reducing admixture was used to maintain the constant level of workability. Slump test following ASTM C143 [33] was conducted to evaluate the demand of dosage of plasticizer in each mixture of concrete against a constant slump value. Target slump value for each mixture of concrete was maintained up to 130 mm. No mix was designed to achieve a particular strength because the study was aimed at relative evaluation of concrete mixes with respect to conventional/control counterpart.

Each concrete mix was blended in a mechanical mixer of 0.15 m^3 capacity. All solid ingredients (binder + sand + aggregates) for each concrete mix, were blended thoroughly in mechanical mixer for about 3 min. Then water and the required amount of plasticizer was added and mixing of concrete continued for further 4 min. RCA were soaked in water for about 30 min and then after air drying were used in the blending process of corresponding RCA concrete mixes. This practice of presoaking RCA, restraint them to absorb any water from fresh binder matrix of concrete. Whereas, NCA were used in air-dried state in the blending of concrete. Since NCA has a very little water absorption than RCA, therefore, NCA were used in air-dried state in the blending process of concrete mixes.

Table 4. Composition of mixes

Series	RCA (%)	FA (%)	MIX ID	OPC (kg/m^3)	FA (kg/m^3)	NFA (kg/m^3)	NCA (kg/m^3)	RCA (kg/m^3)	Water (kg/m^3)	Admixture (kg/m^3)
I	0	0	C1	405	0	607.5	1215	0	202.5	2.75
		20	C2	324	81	607.5	1215	0	202.5	2.65
		40	C3	243	162	607.5	1215	0	202.5	2.58
II	50	0	C4	405	0	607.5	607.5	550	202.5	2.89
		20	C5	324	81	607.5	607.5	550	202.5	2.78
		40	C6	243	162	607.5	607.5	550	202.5	2.75
III	100	0	C7	405	0	607.5	0	1100	202.5	3.12
		20	C8	324	81	607.5	0	1100	202.5	3.08
		40	C9	243	162	607.5	0	1100	202.5	3.03

2.3. Preparation and Testing of Specimens

All concrete mixtures after production were subjected to slump test following ASTM C143 [33] to confirm the required workability. For mixes involving RCA reductions in workability were adjusted using plasticizer. Fresh density by filling a 150 mm cube into three layers (each layer was compacted 25 times using temping rod) was calculated using mass-volume relationship. To evaluate compressive strength of each mixture, cubic specimens of 150x150x150 mm^3 were cast according to BS-EN 12390-3 [34]. After casting specimens were left in molds for 24 hours setting. Then after demolding, all the specimens were cured in water tank at temperature of about 24ºC. Average of three specimens were tested at 3, 28, 90 and 180 days of curing, to estimate the compressive strength of each mixture. All specimens were tested in the CONTROLS compression testing machine of 3000 kN capacity. Overview of slump and compression testing is shown in Figure 3.
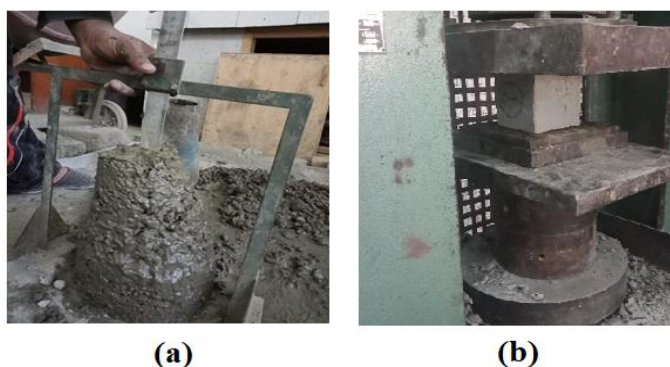

Figure 3. Overview of (a) slump testing and (b) compression testing

2.4. Strength Performance

Strength performance (SP) of each concrete mixture was determined via Equation 1 using the results of compressive strength at the age of 3, 28, 90 and 180 days. The compressive strength of C1 was taken as reference strength as it represents conventional concrete made with 0%RCA and 0%FA. Resulted value from Equation 1 if higher than '100' would indicate better performance than C1, and if lower than '100' would indicate lower performance. Compressive strength was taken as representative of strength parameters because it is most widely used strength parameter in concrete design.

$$SP\ (\%) = \frac{Compressive\ strength\ of\ any\ mixture}{Compressive\ strength\ of\ conventional\ concrete\ mixture\ (C1)} \times 100 \qquad (1)$$

2.5. Economic Performance

To perform economy analysis, cost of 1m^3 of each concrete mixture was calculated by summing the cost of ingredients under each mix. Cost of materials (USD) at the doorstep of the consumer (UET, Taxila) was calculated using the unit price of materials at the hand of supplier plus transportation charges. Cost of transportation was taken as 0.00004 USD/kg/km was estimated by direct quarries from National Logistics and Construction (NLC), Pakistan. Distances of material suppliers from University of Engineering and Technology, Taxila, Pakistan (consumers end) are shown in Figure 4. RCA was manually crushed due to the absence of any recycling plant. Its cost was estimated by analyzing the costs of low-quality coarse aggregates available at different crushing plants in Margalla hills, Taxila, Pakistan. As quality

is one of the prime factors which influence the increase or decrease in the demand for material hence, cost of RCA was estimated by qualitative assessment.

Unit cost of each material used in the experimental study is given in Table 5. Cost of mixing was not covered in this study because investigation was aimed to evaluate economic performance (EP) relatively. EP of each mixture of concrete was ascertained by using Equation 2. As C1 represent conventional concrete, therefore, the cost of each mix was compared with C1. For a mix with EP having greater than '100' would have lower cost than C1, whereas a particular mix with EP value lower than '100' would be having higher cost associated with materials than that of the conventional C1.

$$EP\ (\%) = \frac{Cost\ of\ control\ concrete\ (C1)}{Cost\ of\ any\ concrete\ mixture} \times 100 \qquad (2)$$

Table 5. Cost of materials

Material	Unit cost at supplier's hand (USD/kg)	Transportation cost (USD/kg/km)	Total cost (USD/kg/km) at door-step
OPC	0.085	0.00004	0.08534
FA	0.0017	0.00004	0.0585
River sand	0.0041	0.00004	0.00444
NCA	0.0067	0.00004	0.00704
RCA	0.0042	0.00004	0.00454
Admixture	1.25	0.00004	1.25176
Water	0.0009	-	-

Figure 4. Overview of locations of material suppliers

2.6. Combined Performance (CP)

Cost (or economy) and strength, both are important parameters that are generally considered in designing a particular grade of concrete. Therefore, CP based on strength and economic performance (SP and EP) was evaluated for each of the concrete mixture. CP was calculated at two ages of compression testing i.e. at 28 and 180 days, and this is explained as follows. Conventional concrete 'C1' having binder as OPC reach nearly full potential of its compressive strength at the age of 28 days. But concrete mixes involving FA as partial replacement of cement reach the full potential of strength at extended period of time (this is due to slow nature of pozzolanic reaction between aluminosilicate particles of FA and Ca(OH)$_2$). Therefore, the age of 180 days was also considered in evaluating the CP of each mixture. To evaluate CP concerned with each concrete mixture, values of SP (from Eq.1) and EP (from Eq.2) were used in Eq.3. Value of CP higher than '100' would indicate that a particular mix have better performance than its conventional counterpart, similarly, a particular mix having value of CP lower than '100' would have relatively poor performance than its conventional equal.

$$CP\ (\%) = \frac{EP+SP}{2} \times 100 \qquad (3)$$

3. Results and Discussions

3.1. Workability and Fresh Density

Results of slump testing for all mixtures (both with and without plasticizer) are shown in Figure 5. Whereas, results of fresh density achieved at the target slump of all concrete mixture are shown in Figure 6. General trend indicates that inclusion of RCA reduced both workability and density of fresh concrete. Although RCA were soaked in water prior to using them in the blending process of concrete, but still the workability of RCA mixes was lower than that of the C1. FA improved the workability of concrete, but it slightly influenced the fresh density.
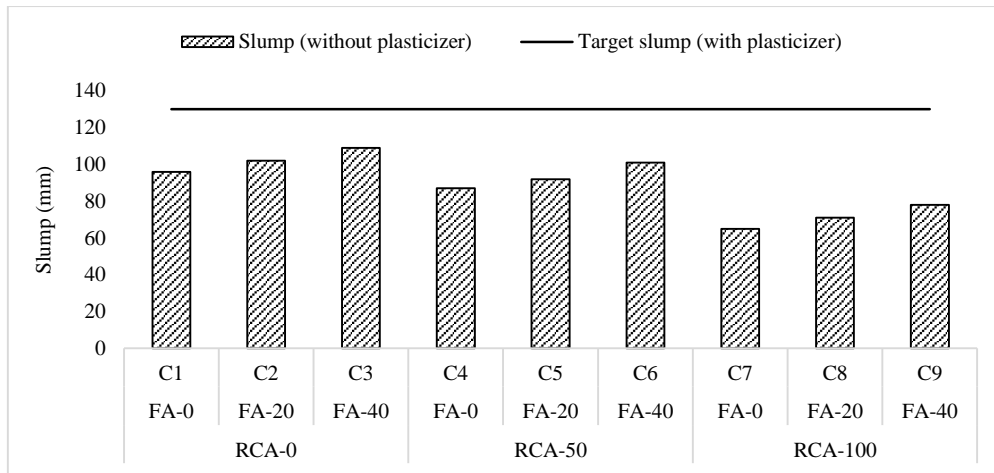

Figure 5. Results of slump testing

As RCA contained low density adhered mortar from parent concrete, reduced the workability and fresh density with each increasing level. RCA are more harsh and irregular-shaped than conventional stone aggregates, therefore they offer lower workability. Presence of low-density adhered mortar from parent concrete in RCA increase the overall porosity of concrete; that is why the fresh density of concrete mixtures reduced with increasing RCA incorporation. RCA mixes have lower fresh density because of the fact that presoaked RCA increase the overall water content of concrete. It is worth mentioning here, to reach the same level of workability, RCA mixes required somewhat higher dosages of plasticizers than that of the mixes having NCA as coarse aggregates. This already has been ascribed to increase in harshness due to RCA in fresh concrete. But the increase in the demand of plasticizer with each increasing level of RCA was insignificant as RCA were already soaked in water before blending of mixes. Kurad et al. [14] reported that RCA mixes have higher water demand than NCA mixes and RCA mixes required higher dosage of plasticizer in order to maintain workability at constant w/c ratio.

FA particles are known for their fine size and spherical shapes; therefore, they act as small ball bearings among coarse grains in cement matrix of fresh concrete. This lubricating action of FA increase the workability of fresh concrete mixtures with each increasing level. FA particles are lighter than cement, but their replacement volume is not huge, therefore FA does not cause significant changes in fresh density of concrete. FA mixes also required lower dosages of plasticizers than C1 to achieve a target level of workability. It is worth mentioning here, role of FA on reduction in the demand of plasticizer was not very significant. It may be concluded that FA particles partly acting as lubricators effectively reduce the demand of plasticizer.
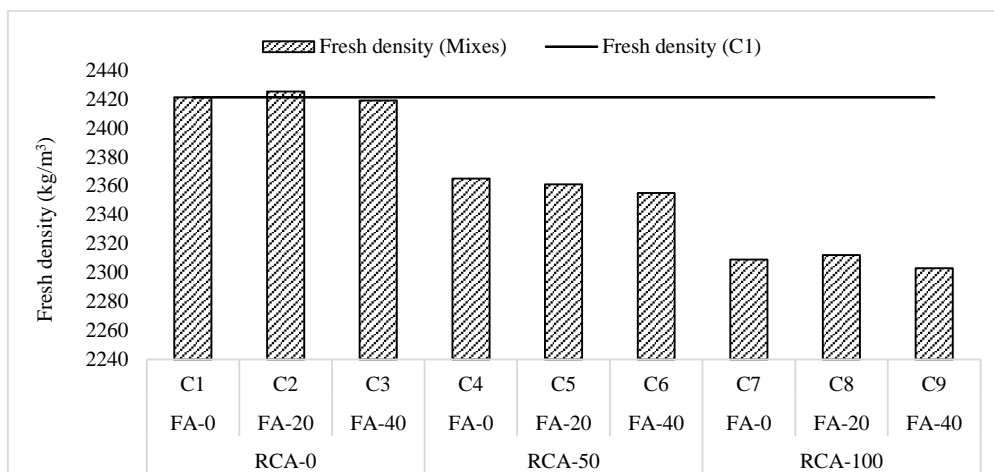

Figure 6. Results of fresh density at target slump

There was a clear contrast in influence of RCA and FA on fresh properties of concrete. RCA reduced the workability and fresh density, whereas FA improved both of the fresh properties. The mixes containing RCA showed little improvements in workability upon the inclusion of FA. As shown in Table 4, the dosage of plasticizer decreased in RCA mixes upon the inclusion of FA. For example, mix 'C6' (made with 40% FA and 50% RCA), and the mix 'C1' had the same demand of plasticizer to achieve the constant level of workability. This can solely be ascribed to positive influence of FA on rheology of concrete. Brito et al. [10] have also reported that FA improves the workability of concrete. It can be concluded that inclusion of FA to some extent compensates the loss in workability due to RCA.

3.2. Compressive Strength

Results of compressive strength for all mixes are shown in Figure 7. The overall trend shows that inclusion of RCA reduced compressive strength at all ages of testing when compared to conventional concrete mixture 'C1'. Whereas loss in early age strength of mixtures involving FA increase with increasing level of FA. But all mixes involving FA (with and without RCA) showed significant improvements in compressive strength at 90, and 180 days.
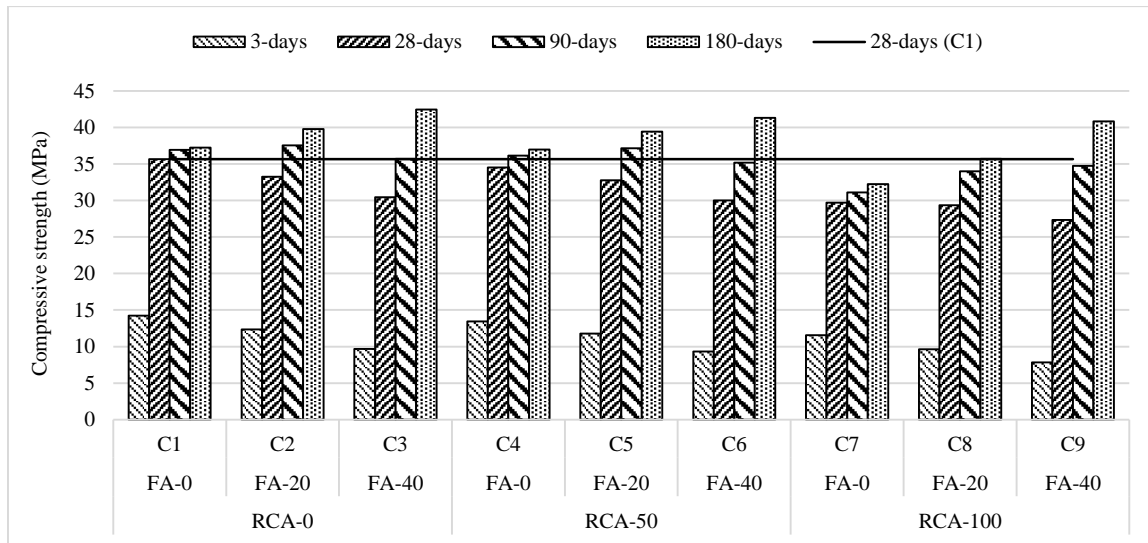

Figure 7. Results of compression testing

The inclusion of RCA as partial replacement of NCA reduced strength primarily because of the presence of low-density mortar in RCA. Increase in overall water content of RCA mixes can also be blamed for lower strength of RCA mixes than that of the C1. Compared to C1, presence of more water in RCA mixes may increase the global porosity of concrete which can be responsible for reductions in compressive strength. Reduction in fresh density of concrete mixes due to RCA also suggest that lessening in compressive strength is inevitable. At 50% level of RCA reductions in the compressive strength at the ages of 3, 28, 90, and 180 days were 6%, 4%, 3%, and 1% respectively. Similarly, reductions in compressive strength at 100% RCA at the ages of 3, 28, 90, 180 days were 19%, 17%, 16%, and 14% respectively. The compressive strength of RCA mixes improved over the period of 180 days. This can be ascribed to the hydration of old cement mortar present in RCA as reported by Kurda et al. [14] which contributes to strength gains in RCA mixes at later ages.

The inclusion of FA reduced the early age (at 3-days) compressive strength by about 14% and 33% at 20% and 40% level of FA respectively. This loss for 20% and 40% FA reduced to about 7% and 15% respectively at the age of 28 days. Unlike younger ages, FA improved later strengths i.e. 90 and 180 days. At the age of 180 days, there was a net increase, in compressive strength, of about 6% and 14% at 20% FA and 40% FA respectively, w.r.t conventional C1. FA mainly act as a pozzolanic binder which means it will slowly react with $Ca(OH)_2$ produced as by product of hydration of Portland cement. Calcium silicate hydrates (C-S-H) are the durable product of hydration of cement along with free $Ca(OH)_2$ as a non-durable product. As FA is rich in silica and alumina, its particles react with $Ca(OH)_2$ and form C-S-H product and add to the overall durable content of cementing products in the matrix of concrete. Pozzolanic reaction is very slow in nature therefore, significant improvements in compressive strength are noticed at later ages only i.e. at 90 and 180 days.

RCA+FA mixes (C5, C6, C8, C9) showed a decline in compressive strength at the age of 3 days, mainly because of FA. As the age of curing increased higher strength gains were noticed at later ages. At the age of 180 days, all RCA mixes involving FA showed better strength properties than conventional 'C1' mix. At the age of 180 days, 100% RCA decreased the compressive strength by about 14% and contrarily FA caused an increase in compressive by about 15%, hence FA compensated the strength loss in RCA mix to a great extent. Concrete mix 'C9' made with 40% FA and 100% RCA showed a net increase in compressive strength of about 9% w.r.t 'C1'. As new and old cement paste in RCA mixes

carry free or unused $Ca(OH)_2$ which may react with FA particles in pozzolanic reaction to produce CSH. So, the net increase in compressive strength of FA+RCA mixes is attributed to the reaction of FA particles with $Ca(OH)_2$ present in both new cement matrix and old cement paste of RCA. Hence it can be inferred that FA can minimize negative influence of RCA on compressive strength of concrete up to a great extent.

Table 6. Loss (+) or gains (-) in compressive strength on individual incorporation of RCA and FA w.r.t C1

Mix ID	RCA/FA	3-days	28-days	90-days	180-days
C2	FA-20%	13.3%	6.8%	-1.7%	-6.8%
C3	FA-40%	32.0%	14.6%	3.3%	-14.0%
C4	RCA-50%	5.5%	3.3%	2.1%	0.7%
C7	RCA-100%	19.0%	16.7%	15.7%	13.4%

Table 7. Prediction of combined effect using the individual effect of RCA and FA

Mix ID	RCA+FA	3-days		28-days		90-days		180-days	
		Predicted	Actual	Predicted	Actual	Predicted	Actual	Predicted	Actual
C5	RCA50FA20	18.9%	17.3%	10.1%	8.1%	0.4%	-0.6%	-6.2%	-5.9%
C6	RCA50FA40	37.6%	34.6%	17.9%	15.9%	5.4%	4.7%	-13.3%	-11.0%
C8	RCA100FA20	32.3%	32.3%	23.5%	17.7%	14.0%	8.0%	6.6%	4.1%
C9	RCA100FA40	51.0%	45.0%	31.3%	23.4%	19.0%	5.9%	-0.6%	-9.7%

Coupling effect of RCA and FA on compressive strength of concrete can be predicted to some extent by summing up their individual effects. For example, at the age of 3 days, reduction in compressive strength w.r.t 'C1' due to 100% RCA (C7) was about 19% and for 40% FA (C3) reduction was about 33%. Their individual effect if summed would result in a total loss of about 52% in compressive strength but actually loss was about 47% in case of 40%FA+100%RCA (C9). Table 7 presents the analysis of predictions of loss or gain in FA+RCA mixes by combining results of individual effects shown in Table 6. At early ages i.e. 3 and 28 days, results of coupling effect are predictable with fair accuracy, but at later ages accuracy reduced. It can be deduced that simultaneously FA and RCA behave differently than their individual behavior on strength of concrete. This is because in RCA+FA mixes chances for FA particles to react with $Ca(OH)_2$ are higher, thus FA+RCA mixes showed higher rates of strength development than FA mixes without RCA.

3.3. Strength Performance (SP)

SP of each mix was calculated using the results of compression testing at the age of 3, 28, 90 and 180 days via Equation.1 are shown in Table 8. At the age of 3 and 28 days, no mixture performed better than 'C1'. As RCA reduced strength at all ages and FA influenced strength at 3 and 28 days severely, therefore no mix outperformed conventional C1. At the age of 90 days, mixes involving 20% FA outperformed C1 by an insignificant margin. At the age of 180 days, nearly all mixes involving FA outperformed C1 by fair/significant margin. All concrete mixtures involving 40% FA outperformed conventional C1 by a very good margin at 180 days. Hence it can be concluded that C5, C6, and C9 are best mixes to outperform conventional concrete by a fair margin.

Table 8. Strength performance of each mix

MIX ID	RCA (%)	FA (%)	SP (3-days)	SP (28-days)	SP (90-days)	SP (180-days)
C1		0	100.0%	100.0%	100.0%	100.0%
C2	0	20	86.7%	93.2%	101.7%	106.8%
C3		40	68.0%	85.4%	96.7%	114.0%
C4		0	94.5%	96.7%	97.9%	99.3%
C5	50	20	82.7%	91.9%	100.6%	105.9%
C6		40	65.4%	84.1%	95.3%	111.0%
C7		0	81.0%	83.3%	84.3%	86.6%
C8	100	20	67.7%	82.3%	92.0%	95.9%
C9		40	55.0%	76.6%	94.1%	109.7%

3.4. Economic Performance (EP)

Unit costs of materials presented in Table 5 were used to calculate the cost of 1 m^3 of each mix under investigation of this research. In Table 10 cost of all ingredients in each mixture and cost of 1 m^3 of each mix is listed. Relative cost of binder, aggregates, and admixture and of 1 m^3 of each concrete mix w.r.t 'C1' is shown in Figure 8.

Incorporation of RCA caused insignificant reductions in total cost of concrete mix w.r.t C1. Cost of aggregates reduced upon the inclusion of RCA as material cost of RCA was less than NCA. But due to the loss in workability of fresh concrete, the cost of plasticizer was augmented. Increasing RCA up to 100% reduced the total cost of concrete by about 7% w.r.t C1. The total increase in the cost of plasticizer was about 13% compared to C1 at 100% RCA level. Hence, it can be said RCA does not reduce the cost of product concrete by a significant margin and cannot be considered as economical replacement of NCA considering equivalent performance.

It is evident that the cost of OPC is highest of all other conventional ingredients of concrete. Reductions in total consumption of OPC by replacing it with a relatively cheaper mineral admixture will bring the huge economy to concrete. Incorporation of FA as replacement of OPC reduced the total cost of concrete more effectively than RCA did. FA did not only reduce the cost of concrete by reducing the cost of binder but also contribute to reductions in the cost of plasticizers. Total cost of 1 m^3 concrete reduced by about 5% and 10% w.r.t C1 at 20%FA and 40%FA respectively.

The combined effect of RCA and FA on the cost of concrete is predictable. A total reduction, in total cost, of about 19% was noticed at 40%FA+100%RCA (in C9). FA reduced the requirement of plasticizer which up-surged in mixes involving RCA. A large portion of the reduction in the total cost of concrete due to FA+RCA can be largely attributed to FA. Compared to RCA when a small portion of OPC was replaced with FA but FA reduced cost efficiently. It is worth mentioning that cost of transportation has a major role in the cost of FA (transportation distance was about 1400 kilometers), if the distance between FA supplier and the consumer is reduced that will cause further reductions in the cost by large margins.

EP of each mix was calculated using Equation 2 and results are presented in Figure 9. Every mix having RCA or FA or RCA+FA performed better than conventional 'C1'. Percentage higher than 100% is an indicator of better performance than a conventional mixture. Mixes involving FA performed more effectively than those having no FA. As already mentioned, that RCA causes some reductions in the cost of aggregate content but increase the cost of plasticizer to maintain a constant level of workability, therefore RCA do not cause any significant drop in total cost. Unlike RCA, the inclusion of FA reduced the cost of binder content efficiently and also caused savings in cost of plasticizer by increasing workability of fresh concrete.

Table 9. Cost of each ingredient under each mix and total cost

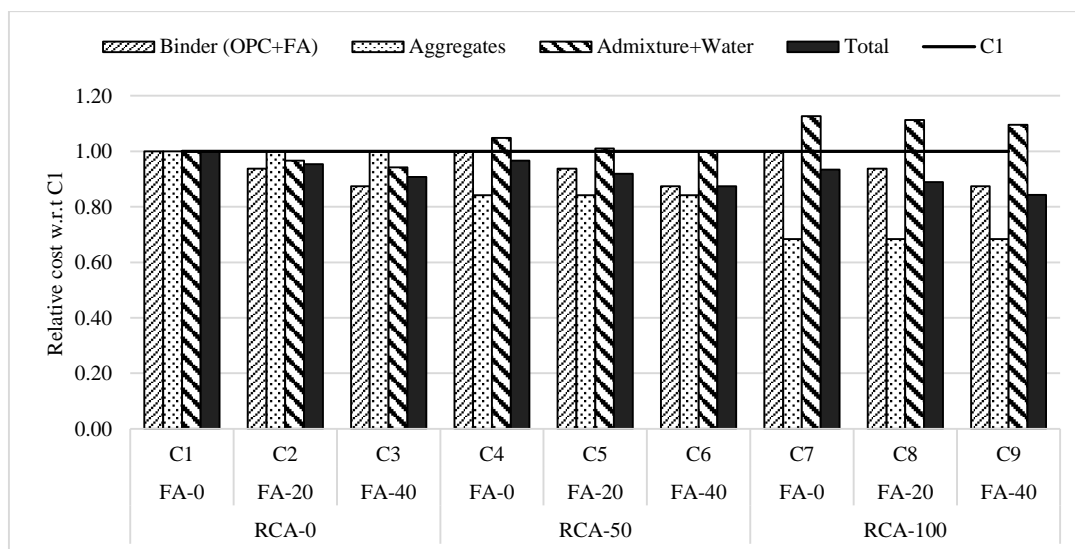| MIX ID	Cost (USD)							
	OPC	FA	Sand	NCA	RCA	Water	Admixture	Total
C1	34.56	0.00	2.70	8.55	0.00	0.18	2.75	48.75
C2	27.65	4.74	2.70	8.55	0.00	0.18	2.65	46.47
C3	20.74	9.48	2.70	8.55	0.00	0.18	2.58	44.23
C4	34.56	0.00	2.70	4.28	2.50	0.18	2.89	47.11
C5	27.65	4.74	2.70	4.28	2.50	0.18	2.78	44.82
C6	20.74	9.48	2.70	4.28	2.50	0.18	2.75	42.62
C7	34.56	0.00	2.70	0.00	4.99	0.18	3.12	45.56
C8	27.65	4.74	2.70	0.00	4.99	0.18	3.08	43.34
C9	20.74	9.48	2.70	0.00	4.99	0.18	3.03	41.12

Figure 8. The relative analysis cost of ingredients of each concrete mix and total cost with reference to C1
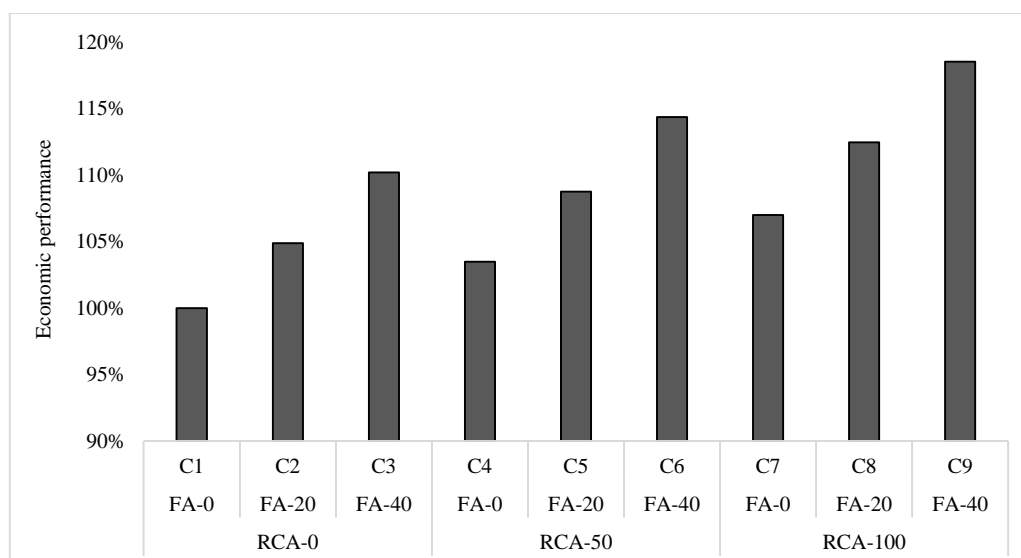
Figure 9. EP of each concrete mixture with respect to C1

3.5. Combined Performance

CP of each mix was calculated incorporating results of SP (at the age of 28 and 180 days) and results of EP in Equation 3. CP of each mixture at 28 and 180 days is given in Table 10. Results of CP showed that most of the mixes underperformed C1 at the age of 28 days. Whereas sufficient improvements in CP were seen for mixes involving FA at the age of 180 days. Although at 50% RCA outperformed nearly all concrete mixtures because of minor reductions in compressive strength at the age of 28 days but CP was reduced by about 5% w.r.t conventional 'C1' at 100% level of RCA. As FA caused savings in total cost of binder and caused significant reductions in the cost of plasticizer, therefore, CP of FA mixes was lower than 'C1' by not a very huge margin. Higher strength gains at the age of 180 days improved CP by about 5% and 13% more than C1 at 20% FA and 40% FA respectively.

The combined influence of FA and RCA was predictable at the age of 28 days. Both FA and RCA caused significant reductions in compressive strength. Only one out of all mixtures having FA+RCA (C5) outperformed C1 at the age of 28 days. At 20% and 40% level, FA improved CP of concrete made with 100% RCA. At the age of 180 days as FA nearly reach its full potential of strength all RCA+FA mixes showed better CP than C1. Higher CP is associated with the mixes involving 40% FA for two reasons; (1) Higher strength gain at the later ages (2) Higher reductions in total cost of concrete. Highest and lowest CP values at the age of 180 days are associated with C7 and C9 respectively. It is worth mentioning all mixes, made with either RCA or FA or with both RCA and FA, did not showed any marginal reductions in CP compared to C1. C7 showed a reduction of about 5% in CP.

Table 10. Results of combined performance analysis

MIX ID	RCA (%)	FA (%)	CP (28-days)	CP (180-days)
C1		0	100.0%	100.0%
C2	0	20	99.0%	105.9%
C3		40	97.8%	112.1%
C4		0	100.1%	101.4%
C5	50	20	100.3%	107.3%
C6		40	99.3%	112.7%
C7		0	95.1%	96.8%
C8	100	20	97.4%	104.2%
C9		40	97.6%	114.1%

4. Conclusions

This research paper investigates the influence of fly ash (FA) and recycled coarse aggregates (RCA) on economic performance of concrete considering its compressive strength. Following conclusions can be drawn from this research paper:

- RCA reduce the workability and density of fresh concrete. On the other hand, FA improve workability and compensates some loss in workability due to the incorporation of RCA in concrete mixtures. By improving

workability FA reduces demand for plasticizers in RCA mixes. RCA affected compressive strength of concrete badly. FA also reduced the early age strength. Both FA+RCA showed higher rates of strength development between 28 and 180 days than FA+NCA and conventional concrete. FA efficiently compensate the compressive strength loss of concrete due to incorporation of RCA.

- Economy analysis indicates that RCA did not cause any significant reductions in the total cost of product concrete, but FA highly contributes to lower the cost of product concrete. FA does not only reduce the cost of OPC but also reduce demand for plasticizers. Economic performance of concrete made with 40%FA and 100% RCA was about 15% higher than that of the conventional concrete.

- Combined economic and strength performance analysis suggests that no concrete mix with individual or combined incorporation of FA and RCA outperform conventional concrete at 28 days. But mixes made with FA and FA+RCA mainly due to higher strength at 180 days and improve the combined performance of concrete by about 13% than that of the conventional concrete.

5. Conflict of Interest

The authors declare no conflict of interest.

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