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RESEARCH ARTICLE

MODELING THE STRENGTH AND ECONOMIC PARAMETERS INVOLVED IN RECYCLING WASTE CONCRETE MATERIAL IN FRESH CONCRETE

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ABSTRACT

The economic and strength implications of concretes made from virgin and recycled waste concrete aggregate in fresh concrete production was examined using concrete mixes of different water cement ratios. The properties investigated were the physical properties and compressive strengths of both concretes and the results of compressive strength showed that the strength of concrete made from recycled aggregate were lower than that made from virgin aggregate but a more important observation was that the rates of gain in strength of concrete made from recycled aggregate approached that of concrete made from virgin aggregate when the free water cement ratio increased from 0.4, 0.45 up to 0.5. But as the water cement ratio increased from 0.55, 0.6 up to 0.65, the difference between the strengths of concrete made from both types of aggregates increased continually with curing age. An economic analysis showed that where a compressive strength in excess of 25N/mm^2 is not needed, the use of recycled aggregate is more economical as Three Thousand Six Hundred Naira can be saved per cubic meter of concrete. Finally, very good fits were obtained for water cement ratios of 0.45, 0.5 and 0.65 using a least square optimization of Scheffe's 2nd degree polynomial.

INTRODUCTION

Waste materials are a common problem in modern living. Wastes accumulate from a number of sources such as domestic and industrial sites. These waste materials have to be eventually disposed of in ways that do not endanger human health and in light of this, waste minimization and also recycling as noted by Cheng, (2000) are increasingly seen as ecologically sustainable strategies for alleviating the need to entirely dispose of waste materials which is often costly, time and space consuming, and can also have significant detrimental impacts on the natural environment. Concrete Waste Materials are described as broken stones of irregular size, shape and texture. The term is closely connected in derivation with rubbish which was formally applied to what we now call rubble (Wikipedia, 2011) and often arises from the demolition, reconstruction and restoration of buildings (Basham 2004). It is estimated that 46% of concrete waste material comes from demolition works, 32% from road works, and the rest from a number of other sources including construction debris (Deal, 1997). In the European Union, it is also estimated that core construction and demolition waste (described as those types of materials which are obtained from demolished building or civil engineering infrastructure) amounts to around 180 million tons per year or 480kg/person/yr (Limbachiya *et al*., 2004). Thus as virgin aggregates become scarcer, and the cost of transportation of both old and new construction materials tend to increase, it is believed that our construction waste can be exploited maximally in terms of recycling. Several researchers have worked on the recycling of waste concrete aggregate in the production of fresh concrete. Shuaibu (2011) studied the effect of partial replacement of virgin aggregates with 0%, 10% and 20% of concrete rubble in the production of fresh concrete. His work which focused more on compressive strength showed that there was a progressive reduction in strength of the concrete made from partially replacement of concrete rubble as compared to that made from virgin aggregates. It is however worthy of note that all the produced concrete met the minimum strength requirement of BS 1881, (1970). Arum, (2011) investigated the characteristics of fresh concrete produced with recycled demolition concrete. The results showed that at higher water-cement ratios, the compressive strength of recycled concrete is similar to that of virgin concrete but at lower water-cement ratios, the compressive strength of recycled concrete is appreciably lower than that of virgin concrete. His results agreed with that of Limbachiya *et al.* (2004). Okafor (2010), while working on recyclability of waste concrete investigated its performance using three concrete mixes of widely differing water cement ratios (0.45, 0.54 and 0.63). His results suggested that both compressive and flexural strengths of concrete made from recycled waste concrete aggregate is dependent on the strength of the original concrete from which the recycled aggregate is derived and also

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lower than the strength of concrete produced from virgin aggregates. This reduction in strength he attributed to the considerable amount of old mortar which always remains attached to the aggregate particles in recycled aggregates. He concluded that recycled aggregate can be used to produce quality concrete when the strength of concrete required is not greater than the strength of the original concrete from which the recycled aggregate is derived. De Juan *et al*. (2009) studied the effect of attached mortar content on the properties of recycled concrete aggregate. He observed that the properties of recycled concrete aggregate adversely affected by attached mortar content are the density, water absorption and Los Angeles abrasion. While Khatib, (2005) while examining the effect of fine recycled aggregate on the properties of concrete showed that there is an observed strength reduction of 15 – 30% for concrete containing fine recycled aggregate and that more shrinkage and expansion occur in these concretes. The emphasis of these studies considered so far has predictably been the workability, strength, safety, environmental friendliness and usage of the material. The present study therefore considers not only the above discussed parameters but goes further to model the strength characteristics of recycled aggregate concrete and to also consider its economic implications per cubic meter.

MATERIALS AND METHODS

Recycled Aggregates

The Construction and Demolition (C&D) concrete aggregates for recycling were obtained from a 15-year old concrete slab of a demolished storey building. A similar method described by Arum, (2011) was used for its preparation although it was soaked in water for seven days before being dried and sieved. The physical properties of the recycled coarse aggregates are shown in Table 1 as determined using BS 812 (1975).

Table 1. Physical Properties of Coarse Aggregate

Physical Property	Aggregate	
	Virgin	Recycled
Specific gravity	2.60	2.42
Aggregate impact value (%)	21.98	30.97
Water absorption (%)	0.20	3.80
Aggregate crushing value (%)	22.41	31.50
Sieve analysis of aggregate by weight passing a set of sieve sizes		
Sieve sizes	Virgin	Recycled
38mm	-	-
25.4mm	85	93
20.0mm	45	60
12.7mm	23	46
9.5mm	10	20
6.4mm	5	8
4.8mm	1	1
3.2mm		
1.25mm		
600µm		
300µm		
15µm		
75µm		

Virgin Aggregates

The virgin aggregates used in the tests were obtained from an approved source (Zone 3) and complied with BS 882 (1975). The coarse aggregate is crushed granite while the fine aggregate is river sand. The physical properties of the coarse aggregate are as shown in table 1 as determined in accordance with BS 812 (1975).

Concrete mix

A nominal mix of 1:2:4 was used to prepare concrete from recycled aggregate and from virgin aggregate. The batching was by weight and the method of BS 882 (1983) was followed. Ordinary Portland cement was used as the binding agent and six mixes were produced using recycled aggregate. The mixes were for water/cement ratios of 0.4, 0.45, 0.5, 0.55, 0.6 and 0.65.

Laboratory testing

The slump test and Compacting factor test were carried out for each of the resulting six mixes. The compacting factor test became necessary as it is a tool used for ascertaining the workability of concrete. While the cube crushing tests were done on standard cube sizes of 150mm with 180 cubes cast such that 90 cubes each were for concrete from recycled and from virgin aggregates respectively. The cubes were prepared, cured and tested for compressive strength in accordance with the recommendations of BS 1881(1975). They were crushed successively at maturity ages of 7,14,21,28 and 56 days for water/cement ratios ranging from 0.4 to 0.65 and the determined compressive strengths shown in Table 3. The compression test machine used was compact – 1500, with a maximum capacity of 1560KN crushing load.

RESULTS

Workability and Compressive Strength

The results of the slump and the compacting factor tests are shown in Table 2 while a summary of the compressive strength values for the two concrete types are presented in Table 3.

Model formulation

The Scheffe's Model for 2nd degree polynomial is as follows:

$$E(y) = \beta_0 + \sum_{i=1}^{p} \beta_i x_i{}^2 + \sum\sum_{i<j}^{p} \beta_{ij} x_i x_j + \cdots + \quad \varepsilon \qquad \ldots\ldots 1$$

Where $E(y) = F_f = f$ (Aggregates, Water-cement ratio),
Let Aggregates variable be x_1 and water-cement ratio variable be x_2,
Number of components of the mixture, p = 2 therefore

$$E(y) \Rightarrow F_f = (x_1, x_2)$$

Expanding Equation 1, we have:

$$\Rightarrow F_f = \quad \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_{12} x_1 x_2 + \beta_{11} x_1^2 + \beta_{22} x_{22}^2 \qquad \ldots\ldots 2$$

The constrain of Scheffe's equation for mixture is that

$$x_1 + x_2 + \cdots x_p = 1$$
$$\Rightarrow x_1 + x_2 = 1 \qquad \ldots\ldots\ldots 3$$

Table 2. Mix Proportions and Workability Results for All Concretes

Type of coarse aggregate	Mix num.	Proportion by weight			Free water cement ratio	Cement content (kg/m^3	Workability		Water in litres
		Ordinary Portland cement	Aggregate Fine	Coarse			Slump (mm)	Compacting factor	
Virgin	1	30	64	118	0. 4	300	20	0.88	120
	2	”	”	”	0. 45	”	33	0. 92	135
	3	”	”	”	0. 5	”	45	0. 92	150
	4	”	”	”	0. 55	”	57	0. 9.4	165
	5	”	”	”	0. 6	”	69	0. 95	180
	6	”	”	”	0. 65	”	80	0. 95	195
Recycled	1	30	64	118	0. 4	300	9	0.82	120
	2	”	”	”	0. 45	”	17	0. 82	135
	3	”	”	”	0. 5	”	22	0. 84	150
	4	”	”	”	0. 55	”	29	0. 84	165
	5	”	”	”	0. 6	”	26	0. 87	180
	6	”	”	”	0. 65	”	43	0. 89	195
For a w/c ratio of 0.4 Water = 120 litres									
Cement= 300Kg/m^3 Fine aggregates= 640 Kg/m^3 Coarse aggregates= 1180 Kg/m^3									

Table 3. Summary of Compressive Strength Results

Aggregate type	Water/cement ratio	Mean compressive strength (N/mm^2)				
		Age (days)				
		7	14	21	28	56
Virgin	0. 4	9.38	12.20	14.10	16.57	20.45
	0. 45	13.78	15.97	17.92	21.23	27.18
	0. 5	13.93	16.61	18.67	23.43	29.12
	0. 55	16.39	20.41	23.65	27.27	35.88
	0. 6	11.25	14.58	17.65	19.41	25.93
	0. 65	7.84	9.68	12.34	14.70	19.02
	0. 4	7.41	9.88	11.40	13.15	17.08
Recycled	0. 45	13.25	14.96	16.75	20.42	24.97
	0. 5	13.39	16.79	18.52	22.92	26.09
	0. 55	14.52	19.44	21.54	25.17	33.47
	0. 6	10.44	12.68	15.28	17.75	22.92
	0. 65	5.76	7.77	9.15	10.65	14.88

Thus, let

$$\beta_0 = \beta_0 \cdot 1 = \beta_0(x_1 + x_2)$$

Also, it can be seen that $x_1^2 = x_1x_1$ and similarly,

$$x_2^2 = x_2 - x_1x_2$$

Therefore we have that

$$F_f = \beta_0(x_1 + x_2) + \beta_1x_1 + \beta_2x_2 + +\beta_{12}x_1x_2 + \beta_{11}(x_1 - x_1x_2) + \beta_{22}(x_2 - x_1x_2)$$
$$= (\beta_0 + \beta_1 + \beta_{11})x_1 + (\beta_0 + \beta_2 + \beta_{22})x_2 + (\beta_{12} - \beta_{11} - \beta_{22})x_1x_2$$

Let $(\beta_0 + \beta_1 + \beta_{11}) = \mu_1$; $(\beta_0 + \beta_2 + \beta_{22}) = \mu_2$; $(\beta_{12} - \beta_{11} - \beta_{22}) = \mu_{12}$;

$$\Rightarrow F_f = \mu_1x_1 + \mu_2x_2 + \mu_{12}x_1x_2 \qquad \dots\dots 4$$

This in a compact form is given as:

$$F_f = \sum_{I<i<p}^{p} \mu_ix_i + \sum \sum_{1<i<j<q}^{p} \mu_{ij}x_i\,x_j \qquad \dots\dots 5$$

Applying the least square principle to equation 5 we now have that:

$$\left.\frac{dL}{d\mu_i}\right|_{(i=1-2)} = -2\sum_{i=1}^{n}\left[F_{fi} - \sum_{I<i<p}^{p}\mu_ix_i + \sum\sum_{1<i<j<q}^{p}\mu_{ij}x_i\,x_j\right] = 0 \qquad \dots\dots\dots 6$$

And

$$\left.\frac{dL}{d\mu_{ij}}\right|_{1<i<j<q} = -2\sum_{i=1}^{n}\left[F_{fi} - \sum_{I<i<p}^{p}\mu_ix_i + \sum\sum_{1<i<j<q}^{p}\mu_{ij}x_i\,x_j\right]x_ix_j = 0 \qquad \dots\dots\dots 7$$

Equations 6 and 7 therefore resulted in a set of homogeneous equations which gave the unknowns: $\mu_i \; and \; \mu_{ij}$

Model equations

The result of the model equations and the corresponding r squared values are shown in Table 4.

Table 4. Summary of Predictive equations

	Virgin Aggregates		Recycled Aggregates	
S/N	Predictive equation	R^2 value	Predictive equation	R^2 value
1	$\sigma_7 = -0.323x_1 - 1192.52x_2 + 15.853x_1x_2$	R^2= 0.9021	$\sigma_7 = -0.393x_1 - 1343.916x_2 + 17.854x_1x_2$	R^2= 0.8112
2	$\sigma_{14} = -0.4426x_1 - 1549.368x_2 + 20.622x_1x_2$	R^2= 0.9137	$\sigma_{14} = -0.477x_1 - 1609.12x_2 + 21.405x_1x_2$	R^2= 0.9157
3	$\sigma_{21} = -0.37x_1 - 1376.858x_2 + 18.38x_1x_2$	R^2= 0.93	$\sigma_{21} = -0.498x_1 - 1690.59x_2 + 22.51x_1x_2$	R^2= 0.613
4	$\sigma_{28} = -0.443x_1 - 1683.59x_2 + 22.44x_1x_2$	R^2=0.9084	$\sigma_{28} = -0.629x_1 - 2122.92x_2 + 28.249x_1x_2$	R^2= 0.605
5	$\sigma_{56} = -0.614x_1 - 2184.6x_2 + 29.183x_1x_2$	R^2=0.911	$\sigma_{56} = -0.697x_1 - 2341.86.92x_2 + 31.24x_1x_2$	R^2= 0.6193

DISCUSSION OF RESULTS

Workability

The results of both the slump test and the compacting factor test show that the workability of recycled concrete is less than that of normal (virgin) concrete at the same water cement ratio. This means that more water (about 6-8%) is needed for recycled concrete to attain the same workability as virgin concrete; this is in agreement with the observations of Okafor, (2010) and is believed to be as a result of the higher proportion of recycled aggregates that is less than 12.7mm.

Compressive strength

Compressive strength results show that at lower water cement ratios, the strength of recycled concrete at various maturity ages investigated is appreciably lower than the strength of virgin concrete. This according to Okafor, (2010) is attributed to the fact that old mortar is always attached to the recycled aggregates and this initiates a failure at a compressive stress somewhat below that of virgin aggregates. At the maturity age of 28 days, the compressive strength of recycled concrete is only 92.3% of virgin concrete at a water cement ratio of 0.55 and at a water cement ratio of 0.65 the compressive strength of recycled concrete is 72.45% of normal concrete. At 7 days the strength of recycled concrete is only about 88.59% of the strength of virgin concrete at a water cement ratio of 0.55 and about 73.47% of the strength of virgin concrete at water cement ratio of 0.65.

In addition to the foregoing, the rates of gain in strength of concrete made from recycled aggregates approaches that of concrete made from virgin aggregates when the free water cement ratio increases through 0.4, 0.45 up to 0.5 which agrees with Okafor, (2010) who observed that as water cement ratio increases, the difference between the strengths of concrete made from both types of aggregates reduces with increase in curing age. But as the water cement ratio increased through 0.55, 0.6 and 0.65, the difference between the strengths of concrete made from both types of aggregates increased continually with curing age which also agrees with the work of Limbachiya *et al*. (2004). Thus one can conclude that any of the two trends is possible depending on the initial moisture content of the aggregates before being used in concrete and also on the water cement ratio of the mix.

Test of significance and compressive strength modeling

The comparison of predicted and observed trends for both virgin and recycled aggregates is shown in Figs 1-4. A test of significance shows that very good fits were obtained for water cement ratios of 0.45, 0.5 and 0.6 while a poor fit was obtained for that of 0.55. This can be attributed to the fact that the least square optimization equation used was that of Scheffe's second degree polynomial which cannot give an exact fit for all the raw data points.

Economic implications

Considering that 92.3% and 72.45% of virgin concrete strength can be achieved by recycled aggregate concrete at water cement ratios of 0.55 and 0.65 respectively for 28days curing age.

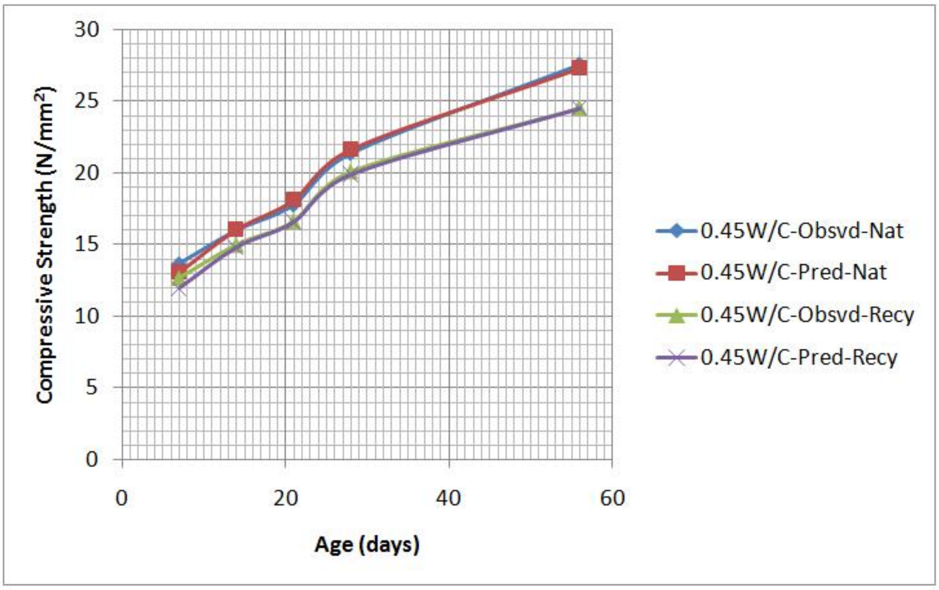

Fig. 1. Comparison of predicted and observed strength for Virgin and recycled aggregates at 0.45 w/c ratio

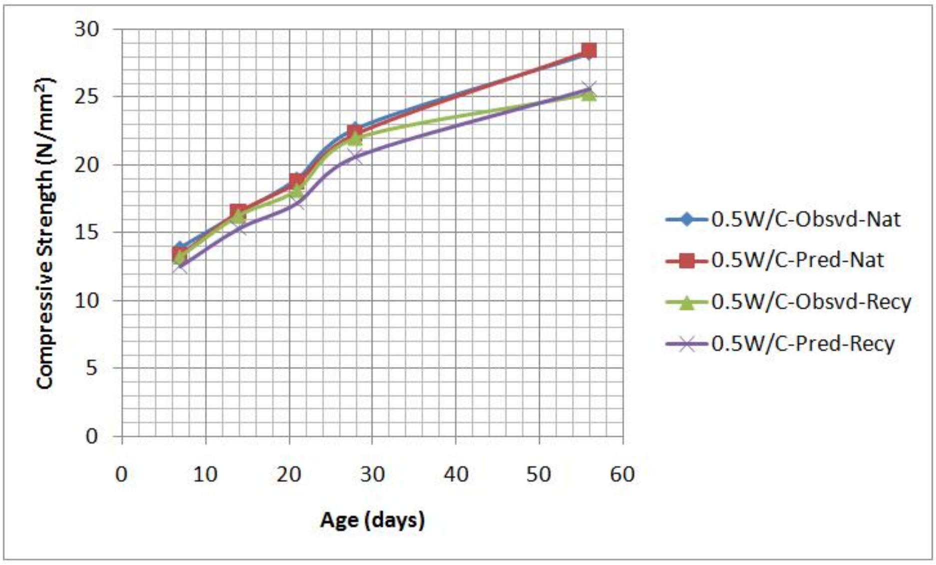

Fig. 2. Comparison of predicted and observed strength for Virgin and recycled aggregates at 0.5 w/c ratio

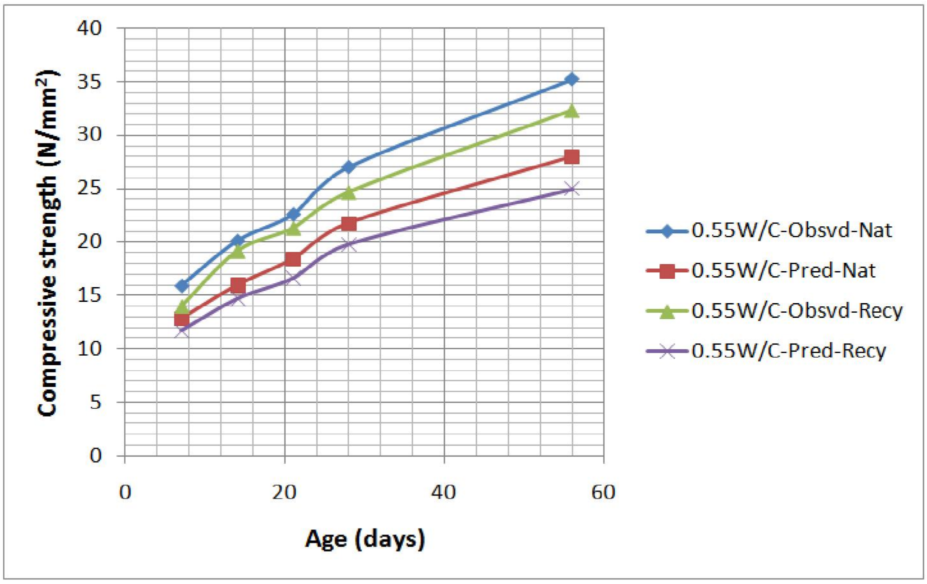

Fig. 3. Comparison of predicted and observed strength for Virgin and recycled aggregates at 0.55 w/c ratio

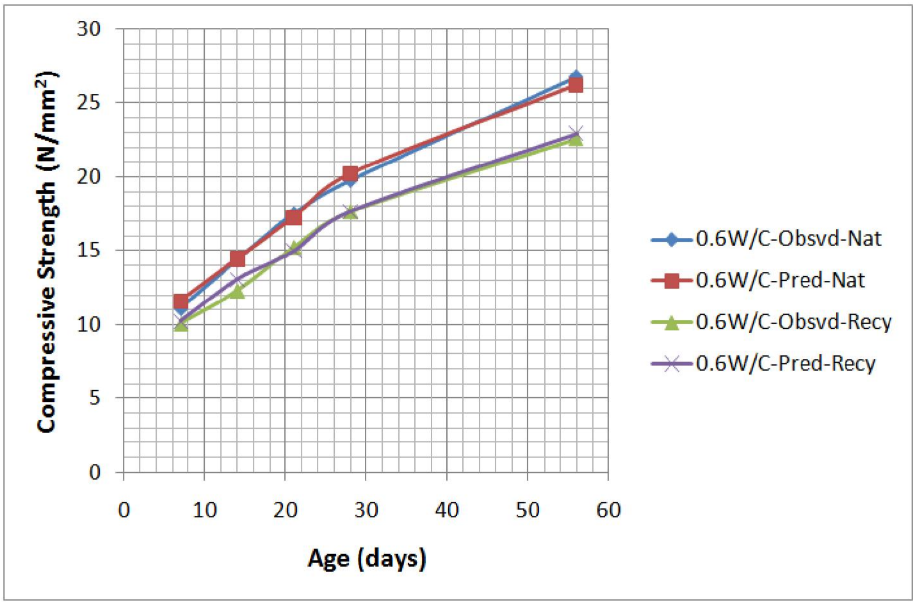

Fig. 4. Comparison of predicted and observed strength for Virgin and recycled aggregates at 0.6 w/c ratio

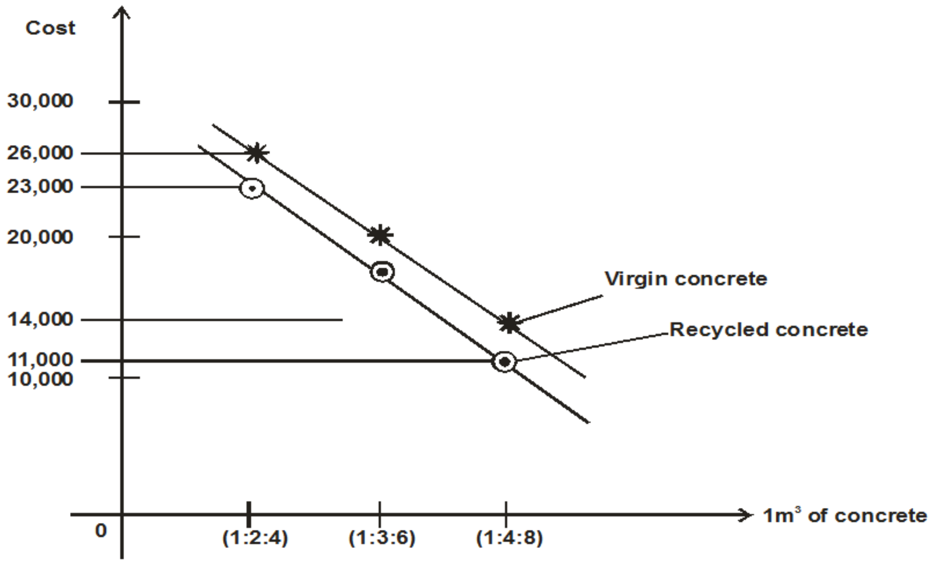

Fig. 5. Cost Analysis of Virgin and Recycled Aggregates

And 88.59% and 73.47% of virgin concrete strength for water cement ratios of 0.55 and 0.65 for 7days curing age. The economic implications of the production of a cubic meter for both types of concrete at 0.55 water cement ratio was therefore investigated and presented in Fig. 5 as both types of concrete met the minimum strength requirement of 20N/mm^2 for 28 days curing strength of BS 1881. It is therefore evident that for concrete structures whose 28 days curing strength do not exceed 25N/mm^2, the concrete made for recycled aggregates would save Three Thousand Six Hundred Naira (#3,600.00) per cubic meter and thus more economical.

Conclusion

The results of this investigation show that:

a) At the same water cement ratio, the workability of virgin concrete is higher than that of recycled concrete.
b) The strength of recycled concrete is lower than or at best very close to the strength of the virgin concrete from which the recycled aggregate is derived.
c) Recycled aggregate generally requires more water (about 6-8%) to achieve the workability of a corresponding concrete produced with virgin aggregate.
d) Recycled aggregate has lower specific gravity, higher water absorption and higher aggregate crushing value than is typical of similar
e) Recycling of concrete waste material presents an opportunity for extracting economic and environmental benefits, ranging from:
   - Reducing the amount of waste generated for disposal,
   - Improving community health and sanitation,
   - Restricting environmental pollution,
   - Promoting environmental awareness, and
   - Creating employment opportunities and additional income-generating activities for women groups and young school leavers who may not get immediate jobs.

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