Difference between Crushed Aggregate Properties from Combined and Individual Waste Sources

Vivian W. Y. Tam¹ and C. M. Tam^{2*}

Abstract

Owing to the comprehensive building redevelopment programmes in Hong Kong, there is a huge volume of concrete waste generated that will soon exhaust all the available landfill areas. As such, recycled aggregate is advocated. However, the use of recycled aggregate has been confined to lower-grade applications until now, such as the lower layers of a pavement structures, e.g. capping and sub-base. The main reason is the variable behaviour of recycled aggregates collected from different sources to be crushed in a centralized recycling plant. This paper applies some international standards to classify recycled aggregates. Aggregates were collected from twelve sources, including ten from demolition sites (Samples 1 to 10), one from Tuen Mun Area 38 centralized recycling plant (Sample 11) and one from ordinary virgin aggregate (Sample 12). From test results, Sample 6, akin to Sample 12 (virgin aggregate), was found to be suitable for all types of construction applications, while Samples 2 and 9 were completely unsuitable as recycled aggregate concrete for any application grades. Sample 11 (Tuen Mun Area 38 centralized recycling plant) was found only suitable for non-structural applications, such as base course, and fill. It is concluded that the different sources of recycled aggregate should preferably be separately crushed and classified rather than processed centrally which will lower their overall quality and limit its application.

Keywords: Recycled aggregate, concrete, classification systems, construction.

¹ Lecturer, School of Engineering, Griffith University, PMB 50 Gold Coast Mail Centre, Queensland 9726, Australia. Email: v.tam@griffith.edu.au, Tel: (61) 7-5552-9278, Fax: (61) 7-5552-8065.

^{2*} Correspondence author, Professor, Department of Building & Construction, City University of Hong Kong, 83 Tat Chee Avenue, Kowloon, Hong Kong. Email: bctam@cityu.edu.hk, Tel: (852) 2788-7620, Fax: (852) 2788-7612.

1. Introduction

Confined extensive extraction of natural resources for building construction jeopardizes the principle of sustainability and has received increasing opposition from environmentalists. The comprehensive building development and redevelopment plans in Hong Kong have aggravated the problem of construction and demolition (C&D) waste generation. To optimize the use of natural resources and concrete demolition waste, there is a need to develop long-term action plans on the use of materials and coordinate the various interests among stakeholders and companies in the construction industry [1]. Recycled products reduce the demands for new materials and components, among which recycled aggregate (RA) is one of the major construction wastes capable of being re-used [2].

At present, almost all concrete waste in Hong Kong is dumped into landfill areas which will be exhausted in the coming years. Reducing waste generation is thus a hard pressing issue. The amount of demolition debris dumped at landfill sites in the United Kingdom is in excess of 20 million tons per annum [3]. The bulk of this material is concrete (50 to 55%) and masonry (30 to 40%) involved with only small percentages of other materials such as metals, glass and timber [4]. A wide potential for the applications of mineral wastes in road and building construction had been identified and many specific applications had been documented. Most of the recycled C&D wastes (about 40 to 50%) are used for filling materials. In, 1993, CIRIA [5] estimate that about 10 million tons of construction waste were recycled in the United Kingdom, mainly for low-grade applications, such as fill materials, each year (see Table 1: **Demolition Waste in Construction** [5]. This value was expected to increase to 17 million tons by 2001 and 24 million tons by 2011 [6]. High-grade utilization such as structural concrete, has been discouraged by the

lack of suitable specifications [7] with only 1.1 million tons of concrete waste being crushed, graded and added to new ready-mixed concrete in the United Kingdom (see Table 1).

<Table 1>

Two major reasons for the unpopularity of adopting RA in high-grade application are: i) disqualified behaviour, such as low strength and toughness, low density and high water absorption; and ii) even when some of the RA have acceptable quality for high-grade applications, their quality may be weakened by mixing with those coming from variable sources delivered to a centralized concrete recycling plant.

2. Research Objectives

To promote the use of RA, aggregate characteristics for various construction applications should be fully apprehended. This paper aims at: i) examining the behaviour of RA from variable sources; ii) exploring the requirements of aggregate for various construction applications; iii) classifying RA for different recycled aggregate concrete applications; and iv) exploring briefly the design of mobile crusher and highlighting the advantages in the use of it for RA production when compared to centralized crushing plants.

3. Properties of Recycled Aggregate

Aggregate generally occupies seventy to eighty percent of the volume of concrete and can, therefore, be expected to have an important influence on its properties [8,9]. Hence, the selection and proportioning of aggregate should be given careful attention. Recycled aggregates are more liable to deformation and less resistant than cement slurry, due to their porosity [10]. As RA has

a larger amount of porosity and can potentially undergo a higher degree of deformation and will be weaker than the cement paste [10], they are greatly affected the mechanical and physical properties of concrete.

Rubble from demolished concrete buildings yields fragments of aggregate which are contaminated with hydrated cement paste, gypsum and minor quantities of other substances. These foreign materials are unsuitable for making fresh concrete mixtures. However, coarse recycled aggregate, although coated with varying cement paste, has been used successfully as recorded in several laboratory and field studies [11]. Previous studies indicate that, compared with concrete containing natural aggregate, the recycled aggregate concrete could still achieve at least two-thirds of the required compressive strength and modulus of elasticity, with satisfactory workability and durability [11].

In order to investigate the properties of RA, there are several tests. They include: i) particle size distribution; ii) particle density; iii) porosity and absorption; iv) particle shape; v) strength and toughness; and vi) chemical composition. The standards used (mainly the British Standards) for assessing properties of aggregate are summarized in Table 2.

<Table 2>

In this study, ten samples of recycled aggregate (Samples 1 to 10) were obtained from ten demolition sites with service lives ranging from ten to forty years while Sample 11 was collected from Tuen Mun Area 38 Centralized Recycling Plant. They were compared with the

performance of ordinary aggregate (Sample 12). A summary of the above-mentioned six property groups for Samples 1 to 12 is shown in Table 3.

<Table 3>

4. Applications of Recycled Aggregate

Although the quality of RA is in general lower than that of ordinary aggregate and varies between sources, the material can still substitute virgin aggregate in structural, minor-structural and non-structural applications. Classification systems for RA mainly include measuring the particle size distribution, particle density, water absorption, ten percent fine value, aggregate impact value, flakiness index, sulphate content and chloride content. The details are described as follows:

- (a) *Grading*: particle size distribution of recycled aggregate is required to be the same as that of normal aggregate. Since the grading plays a significant role in influencing concrete properties, including drying shrinkage, workability of concrete and also the production cost [12]. Therefore, a suitable grading of aggregates should be stipulated according to British Standard (BS) 882 [13-15]. ASTM D2940-03 [16] and ASTM D448-03 [17] are adopted for pavement and embankment, road and bridge respectively.
- (b) *Density* is the most fundamental classification parameter. The lower density of recycled aggregate is due to the existence of porous and less dense residual mortar lumps or particles adhering to the surface of larger aggregate particles. Aggregate density constitutes a very important parameter for accurate batching and concrete mix design, which is influenced by variations in the composition of the recycled materials. Normally, the classification would identify various ranges of density between 2100, 1600 and 1000

kg/m³ [14, 15, 18-20]. Aggregate with density lower than 1,000 kg/m³ would normally not be recyclable.

- (c) *Water Absorption* is also one of the key performance indicators for RA. It is most commonly determined parameter using the twenty-four hour measurement approach, but the ten-minute measurement is also adopted in Germany [18]. In general, the absorption rates of recycled aggregate are highly variable and generally higher than ordinary aggregates. Higher absorption rates pose potential problems for concrete production given that water demand and workability can be severely altered. RA exhibits water absorption higher than 15% is not acceptable in many countries; a maximum of 10% is accepted for many construction applications [14, 15, 19-21]. Pre-wetted recycled aggregate normally offsets inadequate concrete workability resulting from variations in water absorption rates [14,15].
- (d) *Flakiness Index*: thin and flat particles can reduce strength when load is applied to the flat side of the aggregate or across its shortest dimension and are also prone to segregation and breakdown during compaction, creating additional fines. The workability of fresh concrete contained flaky particles may be reduced. In general, flaky materials are not suitable for most applications. The general upper limit for flakiness index of aggregate is 40% by mass [14].
- (e) *Ten Percent Fines Value* reflects the strength performance of aggregate. For heavy-duty concrete elements, aggregate is required to have a value of at least 150kN [22]. For non-structural element and sub-base, the values need to exceed 50kN [14, 23]. A minimum of 100kN is required for recycled aggregate in general [14].

- (f) *Aggregate Impact Value* indicates the resistance of aggregate to sudden impact [24]. A value between 25% and 45% is acceptable. General requirements of 25% are specified for heavy-duty concrete elements [22], 35% for sub-base applications [25,26]; and 30% for other lower-grade applications.
- (g) *Chloride content*: recycled aggregate derived from marine structures or similarly exposed structural elements can induce corrosion of steel reinforcement [27]. Depending on the source of aggregate, chloride may be present in aggregate, either as potassium or sodium salts. A limit on total chloride content is required to minimize the risk of embedded steel reinforcement corrosion and 0.05% adopted in many countries [14,15,19,20]. However, 1% and 0.015% of chloride content are set for non-structural and pre-stressed concrete elements respectively [28].
- (h) *Sulphate content* may give rise to expansive disruption of concrete. Some types of sulphates in recycled aggregate present as cement hydrates in the hardened concrete or residual mortar may be less likely to participate in any further reaction with the new concrete. A limit of less than one percent of sulphate is always applied in various construction applications [14,15,20,23].

According to the BS and ASTM standards, RA used for producing recycled aggregate concrete for the various applications needs to fulfill certain requirements which are summarized in Table 4.

<Table 4>

Table 5 shows a classification system for RA properties, which classifies aggregates into Grades A to G; Grade A represents the highest quality, and Grade G the lowest.

<Table 5>

According to the requirements for different construction applications in Table 5, **Table 6** sets out the minimum grades acceptable for different applications. The twelve samples are classified according to Table 5 with the classification result summarized in **Table 7**.

<Table 6>

<**Table 7**>

From Table 6 and **Table 7**, suitable applications of each aggregate sample are tabulated in **Table 8**. The dry particle density, water absorption, flakiness index and sulphate content of the samples are in general in compliance with the minimum standards with the exception of ten percent fines values, aggregate impact values and chloride content.

<**Table 8**>

As revealed in **Table 8**, Sample 6 can be adopted for all construction applications, including the higher-grade utilization, showing that it is as versatile as the virgin aggregate (Sample 12). On the other hand, two out of the twelve samples (Samples 2 and 9) are completely unsuitable for either higher-grade or lower-grade applications. Meanwhile, since the demolished concrete is collected at a centralized recycling plant at Tuen Mun Area 38 in Hong Kong, the quality of the RA (Sample 11) would be weakened by the averaging effect, restricting them to only non-structural applications such as sub-base course, embankment and fill.

5. Verification of the Classification of RA

In order to verify the above results, the compressive strengths of 100mm sized cubes made from the twelve samples were measured according to BS 1881: Part 116 [29]. The average and the individual results of the three cubes of each sample are tabulated in **Table 9**. Since the limited samples allowed collecting from the various demolition sites, samples verified by the concrete cubes are used as the base. The results show that the compressive strength of recycled aggregate concrete (RAC) made from Sample 6 has reached 59MPa, higher than that made from virgin aggregate (Sample 12) at 56MPa. The lowest strength was recorded for Samples 2 and 9 with values of 46MPa and 47MPa respectively. The test results confirm the validity of the classification system in classifying the quality of aggregates.

<Table 9>

The above demonstrates that the current practice of centralizing RA production can lower their quality. Separation of these concrete wastes by using mobile crushing plants can promote and retain the quality of RA for higher grade applications.

6. Development of Mobile Crusher

In Hong Kong, there is only one recycling plant located in Tuen Mun Area 38. The centralized location facilitates economies of scale. However, this arrangement presents some shortfalls: i) The recycled aggregates produced by the plant are not 100% generated from concrete waste as some of them are from boulders from site formation works. As a result, the behaviour of RA needs to be interpreted with care; ii) Long haulage and transportation time from sites to the

recycling plant; iii) Because of the size of the mega-crushers and screening sieves, stones or concrete wastes smaller than 200mm cannot be trapped by the sieves. This renders some demolition sites experiencing difficulty in complying with the requirement on the minimum size of concrete wastes to be handled; and iv) The averaging effect of the centralized plant will be weakened the potential quality of the aggregates.

In order to fully recycle these concrete wastes from various demolition sites, a mobile crusher is proposed. Within the set-up of a mobile crusher, concrete waste is first crushed by a primary jaw crusher, to reduce the size of stones, followed by passing the material through a magnetic separator before the second crushing by hammer crusher to further reduce the size to 20mm, 10mm and below 5mm. **Figure 1** shows the operation flowchart of the proposed mobile crusher.

<Figure 1>

The mobile crusher is to be housed on a lorry, 7.225m long, 2.375m wide and 3.5m high and weighting 14.59 tons mounted with a grab for loading the concrete waste into the plant and conveyor belts for screening and unloading RA. Using this set-up, the quality of RA can be retained to that of the known source of concrete waste. Therefore, the mobile crusher can open up a wider scope of applications for RA.

7. Conclusion

This paper first examines the six aggregate properties, namely: i) particle size distribution; ii) particle density; iii) porosity and absorption; iv) particle shape; v) strength and toughness; and vi) chemical composition, to classify the RA. The properties of ten RA samples collected from

demolition sites were compared with those collected from Tuen Mun Area 38 Centralized Recycling Plant and ordinary aggregate. The RA collected from one of the demolition sites (Sample 6) was found to be of comparable quality to virgin aggregate, enabling it to be used in high-grade applications. However, two other samples (Samples 2 and 9) are not suitable for any type of application. The classification results were verified by correlation to cube strengths of concrete mixed with the aggregate. This concludes that a centralized recycling plant brings about an averaging effect and thus weakens the quality of RA, restricting the use to non-structural applications such as sub-base course, embankment and fill. A new approach to crush concrete waste-processing using a mobile crusher, is proposed that helps retain the quality of RA to that of the source of concrete waste.

8. Acknowledgments

The work described in this paper was fully supported by a grant from the Housing Authority Research Fund of the Hong Kong Special Administrative Region, China (Project Ref. No. 9460004).

9. References

1. Topping M. Management of concrete demolition waste. *Concrete technology for a sustainable development in the 21st century*. London: New York: E & FN Spon;2000, p.321-331.
2. Edwards B. *Sustainable architecture: European directives and building design*. 2nd ed., Oxford: Architectural Press, 1999.

3. Environmental Resources Limited. *Demolition waste*, Construction Press Limited, Lancaster, England, 1980.
4. Mulheron M. The recycling of demolition debris: current practice, products and standards in the United Kingdom. *Demolition and reuse of concrete and masonry: reuse of demolition waste*, London: Chapman and Hall, 1988, 510-519.
5. Construction Industry Research and Information Association. *Environmental issues in construction: a review of issues and initiatives relevant to the building, construction and related industries*. London: CIRIA, 1993.
6. McLaughlin J. A review of the prospects for the greater use of recycled and secondary aggregates in construction. *Concrete* **27**; 1993, p. 16-18.
7. Collins RJ. Reuse of demolition materials in relation to specifications in the UK. *Demolition and reuse of concrete and masonry: guidelines for demolition and reuse of concrete and masonry: proceedings of the Third International RILEM Symposium on Demolition and Reuse of Concrete Masonry, held in Odense, Denmark, 24-27 October 1993*, London: E & FN Spon; 1993, p. 49-56.
8. Mindess S, Young F, Darwin D. *Concrete*. Upper Saddle River, NJ: Prentice Hall, 2003.
9. Troxell GE, Davis HE. *Composition and properties of concrete*. New York: McGraw-Hill, 1968.
10. Maso JC. Influence of the interfacial transition zone on composite mechanical properties. *Interfacial transition zone in concrete: state-of-the-art report*. London: E & FN Spon; 1996, p.103-116.
11. Mehta PK, Monteiro JM. *Concrete: structure, properties, and materials*. Englewood Cliffs, N.J.: Prentice Hall, 1993.

12. Lai JS. *Materials of construction*. Georgia Institute of Technology, Kendall / Hunt Publishing Company, 4050 Westmark Drive, Dubuque, Iowa 52002, 1999.
13. BS 882. *Specification for aggregates from natural sources for concrete*. British Standards Institution, London, United Kingdom, 1992.
14. BD (Buildings Department) *Practice note for authorized persons and registered structured engineers: use of recycled aggregates in concrete*. Buildings Department, Hong Kong Government, 2003.
15. Hendriks CF, Pietersen HS. *Sustainable raw materials: construction and demolition waste*. Cachan Cedex, France: RILEM Publication, 2000.
16. ASTM D2940-03. *Standard specification for graded aggregate material for bases or subbases for highways or airports*. American Society for Testing and Materials, United States, 2003.
17. ASTM D448-03. *Standard classification for sizes of aggregate for road and bridge construction*. American Society for Testing and Materials, United States, 2003.
18. DIN 4226-100. *Aggregates for mortar and concrete: part 100 recycled aggregates*. Beuth Verlag GmbH, Germany, 2002.
19. Krezel ZA, McManus KJ. *Recycled aggregate concrete-sound absorbing barriers for urban freeways*. Swinburne university of technology, Homepage, available at <http://www.hed.swin.edu.au/ses/administration/staff/bios/krezela4.pdf>, 2002.
20. Vyncke J, Rousseau E. Recycling of construction and demolition waste in Belgium: actual situation and future evaluation. *Demolition and Reuse of Concrete and Masonry: Guidelines for Demolition and Reuse of Concrete and Masonry: Proceedings of the Third*

International RILEM Symposium on Demolition and Reuse of Concrete Masonry. 24-27 October 1993, London: E&FN Spon; 1993, p.57-69.

21. Tomosawa F, Noguchi T. New technology for the recycling of concrete – Japanese experience. *Concrete technology for a sustainable development in the 21st century. London: New York: E & FN Spon, 2000, p. 274-287.*
22. Majid NZA. *The influence of aggregate properties on strength of concrete.* Homepage, available at <http://www.geocities.com/nikzafri/conagg.html>, 2000.
23. WBTC (Works Bureau Technical Circular). *Specifications facilitating the use of recycled aggregates.* Hong Kong Government, 2002.
24. BS 812: Part 112. *Methods for determination of aggregate impact value (AIV).* British Standards Institution, London, United Kingdom, 1990.
25. Kenyon SC. *Market development study for recycled aggregate products.* Waste Reduction Advisory Committee, Thurber Engineering Ltd, 2001.
26. Summers CJ. *Aggregate properties,* Homepage, available at <http://www.highwaysmaintenance.com/aggtxt.htm>, 2002.
27. Yrjanson W. *Recycling of Portland Cement Concrete Pavements.* National Cooperative Highway Research Program Synthesis of Highway Practice 154, Transportation Research Board, Washington, D.C., Homepage, available at <http://www.tfhrc.gov/hnr20/recycle/waste/rcc2.htm>, 1989.
28. Sym R. *Testing of industrial products - Aggregates for construction.* P & S Research Ltd, Homepage, available at <http://projects.bre.co.uk/aggregate/Cltest/Clprecsn.htm>, 2004.
29. BS 1881: Part 116. *Method for determination of compressive strength of concrete cubes.* British Standards Institution, London, United Kingdom, 1983.

30. BS 812: Part 2. *Methods for determination of density*. British Standards Institution, London, United Kingdom, 1995.
31. BS 812: Part 105.1. *Flakiness index*. British Standards Institution, London, United Kingdom, 1989.
32. BS 812: Part 111. *Methods for determination of ten per cent fines value (TFV)*. British Standards Institution, London, United Kingdom, 1990.
33. BS 812: Part 117. *Methods for determination of water-soluble chloride salts*. British Standards Institution, London, United Kingdom, 1988.

Table 1: Demolition Waste in Construction [5]

Products	Million Tons Reused as Aggregate		Million Tons Recycled as Product	Million Tons Reprocessed
Concrete	6.1	As Fill	-	1.1
Concrete Blocks	2.4	As Fill	-	-
Bricks	1.3	As Fill	0.2	-
Wood	Burnt on Site	-	Special Items	Not Available
Plasterboard	Not Available	-	-	-
Concrete Roof Tiles	0.2 as Fill – in Concrete	-	0.03	-
Cement	Not Available	-	-	-
Plaster	Not Available	-	-	-
Gypsum	Not Available	-	-	-
Steel	-	-	Not Available	0.27
Concrete Pipes	0.1	As Fill	-	-
Other	Not Available	-	Not Available	Not Available
Total	10	As Fill	0.22	1.37

Table 2: Standards for Assessing Properties of Aggregate

Properties of Aggregate	International Standard
<u>Particle Size Distribution</u>	
Sieve Analysis	BS 882 [13]
<u>Particle Density</u>	
Particle Density on Oven-Dried Basis	BS 812: Part 2 [30]
<u>Porosity and Absorption</u>	
Water Absorption	BS 812: Part 2 [30]
<u>Particle Shape</u>	
Flakiness Index	BS 812: Part 105.1 [31]
<u>Strength and Toughness</u>	
Ten Percent Fine Value (TFV)	BS 812: Part 111 [32]
Aggregate Impact Value (AIV)	BS 812: Part 112 [24]
<u>Chemical Composition</u>	
Chloride Content	BS 812: Part 117 [33]
Sulphate Content	Ion Chromatography

Table 3: Summary of Properties of Aggregates for Samples 1 to 12

Sample	Particle Size Distribution		Particle Density		Porosity and Absorption		Particle Shape		Strength and Toughness		Chemical Composition		
	Sieve Analysis		Particle Density on an Oven-Dried Basis (Mg/m ³)		Water Absorption		Flakiness Index (%)		TFV (kN)	AIV (%)	Chloride Content (%)		Sulphate Content (%)
	10mm	20mm	10mm	20mm	10mm	20mm	10mm	20mm			10mm	20mm	
1	Pass	Pass	2.16	2.20	5.83	6.89	11.13	9.68	93.89	33	0.0078	0.0089	0.031
2	Pass	Pass	2.22	2.14	6.36	6.40	10.44	10.08	61.36	36	0.0108	0.0091	0.017
3	Pass	Pass	2.20	2.18	7.50	7.35	15.17	8.61	107.42	31	0.0013	0.0019	0.005
4	Pass	Pass	2.20	2.20	6.93	7.25	15.42	7.91	112.82	23	0.0019	0.0019	0.005
5	Pass	Pass	2.15	2.19	7.31	6.82	17.82	12.96	92.09	32	0.0054	0.0061	0.006
6	Pass	Pass	2.25	2.27	5.20	5.77	11.96	9.93	155.53	25	0.0008	0.0025	0.006
7	Pass	Pass	2.11	2.13	8.74	7.30	12.86	5.70	110.18	30	0.0976	0.0902	0.013
8	Pass	Pass	2.10	2.12	8.58	7.99	15.12	9.78	83.48	34	0.0013	0.0014	0.005
9	Pass	Pass	2.21	2.24	6.94	6.11	13.78	12.17	92.87	36	0.0459	0.0352	0.024
10	Pass	Pass	2.20	2.23	6.85	5.95	16.47	9.92	89.91	28	0.0494	0.0430	0.018
11	Pass	Pass	2.46	2.53	2.63	1.65	25.97	29.52	102.97	33	0.0021	0.0070	0.008
12	Pass	Pass	2.59	2.62	0.77	0.57	28.27	22.52	189.38	21	0.0012	0.0016	0.003

Table 4: Requirements for Various Construction Applications

Properties	Structural Element	Minor-Structural Element	Non-Structural Element	Pre-Stressed Concrete Element	Road Surface	Base Course	Embankment and Fill	Insulation Barrier
Grain-Size Qualification	BS 882 [13]	BS 882 [13]	BS 882 [13]	BS 882 [13]	ASTM D448-03 [17]	ASTM D2940-03 [16]	ASTM D2940-03 [16]	BS 882 [13]
Minimum Particle Density (kg/m ³)	2,000	2,000	2,000	2,000	2,000	2,000	2,000	2,000
Maximum Water Absorption (%)	10	10	10	10	10	10	10	10
Maximum Flakiness Index (%)	40	40	40	40	40	40	40	40
Minimum Ten Percent Fine Value (kN)	150	100	50	100	100	50	50	100
Maximum Aggregate Impact Value (%)	25	30	35	25	30	35	35	30
Maximum Chloride Content (%)	0.05	0.05	1	0.015	0.05	0.05	0.05	0.05
Maximum Sulphate Content (%)	1	1	1	1	1	1	1	1

Table 5: Grading/Classification of Aggregate

Properties	Classification						
	A	B	C	D	E	F	G
Particle density (Mg/m ³)	Above 2.50	2.49-2.40	2.39-2.30	2.29-2.20	2.19-2.10	2.09-2.00	Below 2.00
Water absorption (%)	Below 1.0	1.1-3.0	3.0-5.0	5.1-7.0	7.1-9.0	9.1-10.0	Above 10.0
Flakiness index (%)	Below 8	9-16	17-22	23-28	29-34	35-40	Above 40
Ten percent fine value (kN)	Above 150	149-120	119-110	109-100	99-80	79-50	Below 50
Aggregate impact value (%)	Below 20	21-23	24-26	27-28	29-31	32-35	Above 35
Chloride content (%)	Below 0.015	0.016-0.030	0.031-0.050	0.051-0.100	0.101-0.500	0.501-1.000	Above 1.000
Sulphate content (%)	Below 0.015	0.016-0.030	0.031-0.050	0.051-0.100	0.101-0.500	0.501-1.000	Above 1.000

Table 6: Minimum Grades for Different Construction Applications

Properties	Structural Element	Minor-Structural Element	Non-Structural Element	Pre-Stressed Concrete Element	Road Surface	Base Course	Embankment and Fill	Insulation Barrier
Particle Density	F	F	F	F	F	F	F	F
Water Absorption	F	F	F	F	F	F	F	F
Flakiness Index	F	F	F	F	F	F	F	F
Ten Percent Fine Value	A	D	F	D	D	F	F	D
Aggregate Impact Value	C	E	F	C	E	F	F	E
Chloride Content	C	C	F	A	C	C	C	C
Sulphate Content	F	F	F	F	F	F	F	F

Table 7: Classifications of Samples 1 to 12

Sample	Particle Density		Porosity and Absorption		Particle Shape		Strength and Toughness		Chemical Composition		
	Particle Density on an Oven-Dried Basis (Mg/m ³)		Water Absorption (in % of dry mass)		Flakiness Index (%)		TFV (kN)	AIV (%)	Chloride Content (%)		Sulphate Content (%)
	10mm	20mm	10mm	20mm	10mm	20mm			10mm	20mm	
1	E	D	D	D	B	B	E	F	A	A	C
2	D	E	D	D	B	B	F	G	A	A	B
3	D	E	E	E	B	B	D	E	A	A	A
4	D	D	D	E	B	A	C	B	A	A	A
5	E	E	E	D	C	B	E	F	A	A	A
6	D	D	D	D	B	B	A	C	A	A	A
7	E	E	E	E	B	A	C	E	D	D	A
8	E	E	E	E	B	B	E	F	A	A	A
9	D	D	D	D	B	B	E	G	C	C	B
10	D	D	D	D	C	B	E	D	C	C	B
11	B	A	B	B	D	E	D	F	A	A	A
12	A	A	A	A	E	D	A	B	A	A	A

Table 8: Suitability of Various Construction Applications for Samples 1 to 12

Sample	Structural Element	Minor-Structural Element	Non-Structural Element	Pre-Stressed Concrete Element	Road Surface	Base Course	Embankment and Fill	Insulation Barrier
1			√			√	√	
2								
3		√	√		√	√	√	√
4		√	√	√	√	√	√	√
5			√			√	√	
6	√	√	√	√	√	√	√	√
7			√					
8			√			√	√	
9								
10			√			√	√	
11			√			√	√	
12	√	√	√	√	√	√	√	√

Table 9: Compressive Strengths of Recycled Aggregate Concrete from Samples 1 to 12

Sample	Test	Compressive strength (in MPa)
1	1	51
	2	53
	3	52
	Average	52
2	1	46
	2	47
	3	46
	Average	46
3	1	53
	2	53
	3	52
	Average	53
4	1	50
	2	51
	3	51
	Average	51
5	1	52
	2	51
	3	51
	Average	52
6	1	58
	2	60
	3	58
	Average	59
7	1	51
	2	50
	3	48
	Average	50
8	1	49
	2	52
	3	50
	Average	50
9	1	48
	2	48
	3	45
	Average	47
10	1	53
	2	51
	3	53
	Average	52
11	1	52
	2	52
	3	52
	Average	52
12	1	54
	2	55
	3	57
	Average	56

Figure 1: Operation Flowchart of Mobile Crusher