RECYCLED AGGREGATE CONCRETE WITH FLY ASH: A PRELIMINARY STUDY ON THE FEASIBILITY OF A SUSTAINABLE STRUCTURAL MATERIAL

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I. Introduction

Sustainable construction practices are beginning to gain popularity in the United States where the enormous impacts of the construction industry on natural resource consumption and waste generation is being more closely scrutinized. One of the principle aspects of sustainability is to maximize the use of natural resources and minimize the generation of unusable waste. High volume fly ash concrete technology has proven to be a sound sustainable alternative to ordinary portland cement concrete due to the improved engineering performance and reduced burden on the environment. The incorporation of high volumes of fly ash in concrete mixtures is the first step towards a sustainable concrete -- the incorporation of recycled aggregate is the next step.

The United States Environmental Protection Agency estimates that 136 million tons of building-related construction and demolition (C&D) debris were generated in 1996[1], this does not include waste from roads, bridges or other paving applications which would only increase this number. Building demolitions account for 48% of the C & D waste stream, 33% from non-residential sources and 15% from residential sources. The EPA analyzed the waste generated from 19 non-residential demolitions and found that on average 66% of it was concrete. A similar analysis of residential demolitions found that 24% was concrete. Based on the above numbers the amount of concrete generated from building demolitions in 1996 was 34.5 million tons.

Though an estimated 20-30% of C&D waste was recycled in 1996, the majority of recycling activity was for metals. Several barriers to concrete recycling exist, the most prevalent being the cost of crushing, grading, dust control and separation of unwanted materials[2]. Socio-political barriers are more important in the USA than they are in Europe and Japan where natural aggregate resources have been more scarce over the past decade. The majority of research on recycled aggregate concrete (RAC) is from outside of the USA and though a comprehensive review of research results has shown RAC to be a feasible structural material[3], there are limited examples of its use in this country.

The need for sustainable structural materials is becoming increasingly apparent in the state of California. With the recent construction boom a large number of older buildings have been demolished to make room for new construction. The landfilling of construction waste cannot continue without bound because the costs of landfilling materials, both economic and environmental, continue to rise. Passed in 1989, Assembly Bill 939 recognized these rising costs and mandated that California cities reduce their solid waste output 50% by the end of the year 2000. Many cities have yet to achieve this reduction and it won't be long before the construction industry is expected to contribute significantly to achieving the mandate. This, in combination with the increasing scarcity of natural aggregate resources makes it necessary to consider the feasibility of using recycled concrete as aggregate.

II. Demolition and Production of Crushed Concrete Aggregate

The most important issues in the demolition phase are the separation of different qualities of original concrete and the removal of non-concrete materials[4]. Though mix design information is likely unavailable at the time of demolition, a visual inspection of the concrete can be useful in determining its suitability for use as a high quality aggregate. Ideally the finishings would be removed from the concrete before demolition proceeded so that the only material left to separate would be reinforcing steel. The probability of contamination by drywall, wood, brick and other non-metallic materials is high, though after grinding the majority of these materials will be part of the fine aggregate fractions. This is one of the motivations against the incorporation of recycled concrete fines in concrete production. Metallic materials are easily separated by magnets and are often separated on the demolition site due to the market value of recycled metals. Typical separation methods for lighter, non-metallic materials include hand sorting, vertical air separators and separation by water[5].

A number of different crushers were studied in a Dutch investigation to determine how well they performed in crushing old concrete. Jaw crushers were found to provide the best grain size distribution for concrete production.

Quality

One of the major quality issues in the production of recycled aggregates is the presence of impurities. While the required value of concrete slump can be obtained with a well graded recycled aggregate regardless of the quantity of impurities, the development of strength can be severely altered by impurities. In order of most to least detrimental the impurities of importance are: PVA paint (polyvinyl acetate or latex), asphalt, gypsum hydrate, wood, soil and plaster. Overall, aggregates made from raw materials which contain at least 95% concrete will usually be clean enough to meet specifications without being washed.

The amount of attached mortar varies depending on the size fraction of the aggregate and tends to increase with decreasing particle size. Original concrete quality has much less effect on the amount of attached mortar than the particle size does. The amount of attached mortar for the 5/8" to 1 1/4" size fractions is typically between 20 and 30% by weight. This means that recycled aggregate batched by volume will contain significantly less actual rock than a comparable volume of virgin aggregate. This leads to reduced elastic modulus and increased drying shrinkage.

Physical Characteristics

Absorption and density of recycled concrete aggregates are directly related to the amount of attached mortar, and therefore change with particle size. The density of recycled aggregates is generally between 145 and 155 lb/ft^3. Absorption of recycled aggregates is typically much higher than that of virgin aggregates and is the most significant difference in physical properties between the two. Absorption of the coarse fractions is generally in the range of 4 to 7%, while the fine fractions tend to absorb significantly more water, typically between 8 and 12%. Japanese proposed standards for the use of recycled concrete aggregates limit the absorption of coarse and fine particles to 7 and 13% respectively[6]. Several studies on the Los Angeles Abrasion loss characteristics have shown that all but the poorest quality recycled aggregates meet the ASTM and British Standard 882 requirements.

III. Background on Engineering Properties

A review of available literature on recycled aggregate concrete (RAC) was undertaken to establish the current state of knowledge. There were no available publications on the use of the high volume fly ash system in conjunction with recycled aggregate, thus the following summary is for 100% portland cement RAC.

Mechanical Properties

Compressive Strength

The compressive strength of recycled aggregate concrete (RAC) is generally thought to be lower than that of natural aggregate concrete (NAC). Many researchers have tested RAC in comparison to the original concrete that the aggregate was made from and found strength reductions to be between 8 and 24%, though the average reduction was 10%[7]. Other studies found no reduction in strength and in some cases even an increase in strength [8,9]. Typical conclusions for strengths up to 30 MPa (4400 psi) are that the use of recycled coarse aggregate has a minor effect on strength but as design strength increases, strength reductions up to about 10% are seen; for recycled fine aggregates the effects are amplified.

Kikuchi et al. studied 84 types of recycled aggregate concrete and concluded that RAC showed a linear increase in strength with decreasing water-cement ratio up to strengths of 70 MPa (11,700 psi) and that the strengths were of the same quality as the original concretes. The only observed influence of water-cement ratio of original concrete on RAC strength was when very low strength original concretes were used[10].

The problem with this approach to strength comparison is that the original concrete strength must be known. This is impractical when considering the large scale production of recycled aggregates from various sources. It is more important to compare a typical sample of recycled aggregate with a typical sample of natural aggregate in comparable mix designs (with the same water-cement and coarse-fine aggregate ratios). What is necessary to learn is whether or not RAC can reach satisfactory compressive strengths for structural applications, which almost every one of theses studies has shown but few of them have emphasized. Early studies by Malhotra[11] concluded that satisfactory concrete can be made with recycled aggregates and that any strength reductions could be accounted for in mix proportions. A study by Limbachiya et al. found the ceiling strength of RAC to be about 75 MPa (11,000psi).

Tensile Strength

There is significantly less data on the tensile strength of RAC. Results from a US study of recycling highway pavements found that splitting tensile strengths of several types of RAC made from two different pavements were consistently the same as or greater than the tensile strength of the control experiments which used crushed limestone[12].

Elastic Modulus, Creep and Drying Shrinkage

Due to the comparatively low modulus of elasticity of the attached mortar, the modulus of elasticity of RAC is always lower than that of NAC. Most researchers report a 15% reduction in elastic modulus when either recycled fines or recycled coarse aggregates are used. The use of both recycled fines and recycled coarse aggregates will reduce the modulus further, as will decreasing aggregate quality[13].

Since creep of concrete is proportional to the amount of mortar in the hardened material it is not surprising that RAC has a higher creep than NAC. Several researchers have found creep to be 25 to 50% higher in recycled coarse aggregate concretes, and a further increase due to the incorporation of fines can be expected[14]. Drying shrinkage is similarly affected and has generally been found to be anywhere from 20 to 100% more for RAC compared with NAC.

Durability

A few researchers have concluded that reinforcement in RAC may corrode faster than in conventional concrete, however the most important factors remain to be the water-cement ratio, cement content and depth of cover. The corrosion rate appears unaffected by the type of aggregate once corrosion has started.

A research program conducted on recycled ASR affected highway pavement from Wyoming[15] studied concrete mixtures with low alkali cement (<0.60%), 20% fly ash and crushed limestone in addition to the affected aggregate. Recycled coarse aggregate comprised 65% of total coarse content and recycled fines 22% of total fines content. These RAC samples were compared to samples containing the original aggregate and the expansion according to ASTM 1260 was 11% lower for the RAC.

Properties of Fresh Concrete

The general consensus on the properties of fresh RAC are: 1) concretes made with recycled coarse aggregates require approximately 5% more water to achieve the same workability as NACs due to the surface texture and angularity; 2) the addition of recycled fines increases the water requirement to 15% more than a NAC; 3) pre-soaking of recycled aggregates can help workability and reduce the accelerated setting times and rapid slump losses experienced with dry recycled aggregates; 4) RAC mixtures using more than 50% recycled coarse or 30% recycled fines tend to be harsh and have lower cohesiveness than NAC mixtures

One researcher found that the addition of fly ash and superplasticizer could overcome the increased harshness and reduced cohesiveness of a typical RAC mixture[16]. Other researchers have noted that the angularity of crushed concrete coarse aggregates contributes significantly to the reduced workability and suggest that careful attention to grading can overcome this[17].

IV. High Volume Fly Ash Recycled Aggregate Concrete

Experimental Objective

The objective of the following research program was to verify the feasibility of using recycled aggregate in the production of structural concrete in the Bay Area. High volumes of fly ash (50% by weight of total cementitious material) were incorporated into the mix not only for sustainability reasons, but also for the many known benefits that fly ash brings to both fresh and hardened concrete performance. Since the literature review revealed that recycled concretes are generally of a lower quality than their virgin counterparts, it was hoped that the utilization of fly ash would help to offset the inherent disadvantages of using recycled material.

The high volume fly ash system developed by CANMET researchers ahas proven to improve almost every property of both fresh and hardened concrete[18]. Some of the most important benefits of fly ash are better workability, and increased long term strength and durability. A high-volume fly ash mixture reacts more slowly than a 100% portland cement mixture and therefore reduces the amount of thermal cracking, leading to overall durability improvements. The small particle size of fly ash and its natural reaction with the most porous hydration products of hydrated portland cement further improve the concrete quality through increased impermeability. Fresh concrete properties are also improved due to the "ball bearing" effect of the spherical ash particles. These advantages clearly have the potential to make recycled aggregate concrete of a higher quality than what is normally achieved with 100% portland cement mixtures.

The aim was to produce a 4000 psi mix at 28-days. The testing program included compressive strength tests at 2, 5, 7, 28, 56, 90 and 180 days; splitting tension strength tests at 28, 56, 90 and 180 days; static elastic modulus tests at 28, 90 and 180 days; and drying shrinkage measurements up to 56 days. The recycled aggregate was also characterized to determine the density and absorption characteristics.

Characterization of the Recycled Aggregate

Source

All crushed concrete aggregate samples were obtained from a local supplier of both natural and recycled crushed rock. The original concrete is largely from building demolition projects in the San Francisco Bay Area. Two qualities of concrete are processed at the site. Visual inspection of the concrete leads to the classification of "high" or "low" quality. Low quality concrete includes very porous material and material contaminated by oils, brick or other residues that would be difficult to separate. There are no further procedures for determining the original concrete quality.

The low quality aggregate is stored separately for later processing, or rejected and sent to a landfill depending on the level of contamination. Unwanted materials are manually removed from the high quality concrete , and the material is then conveyed through a series of magnets to remove smaller metallic pieces. Since rebar is easily recycled, it is often separated from the concrete at the demolition site before the concrete is hauled away. Steel collected from incoming concrete is sold to a recycling facility.

A jaw crusher is used to crush the material to a maximum size of 1" and the subsequent material separated for both coarse and fine aggregate applications. The 1" x #8 coarse aggregate was studied in the following testing program; it is usually sold as base drain rock for pavement applications.

Physical Characteristics

The crushed concrete aggregate can be categorized into three types: rocks with no visible attached mortar, rocks with some attached mortar, and pieces of mortar which may or may not contain smaller coarse aggregate portions. The BSG (Bulk Specific Gravity) was 14% lower than the virgin aggregate at 2.47 and the absorption was almost four times that of the virgin aggregate at 5%.

Mix Designs and Mixing Procedures

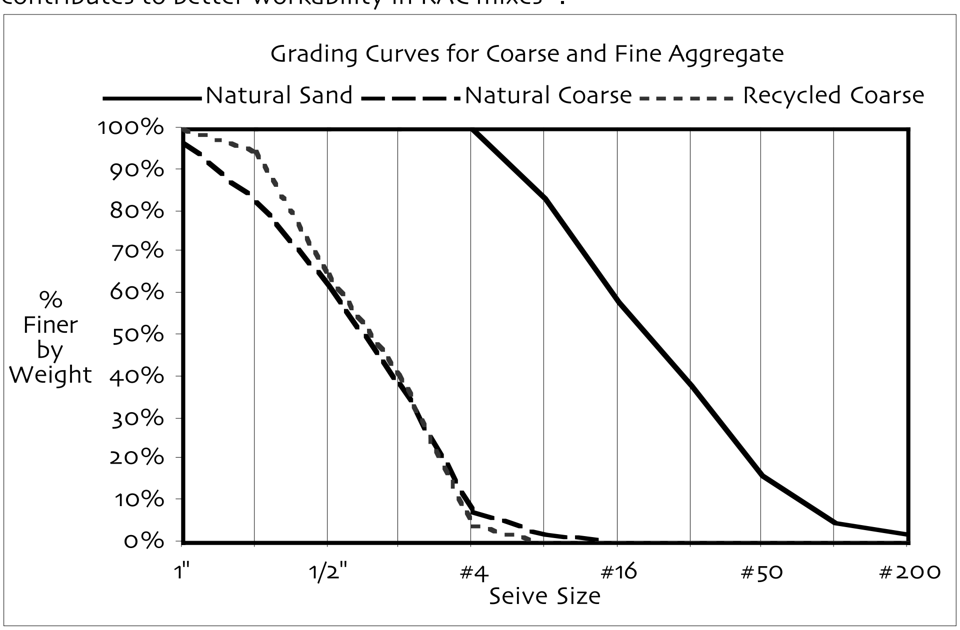
Coarse and Fine Aggregates

Final mixes were batched, mixed and initially cured at the Shamrock Materials laboratory in Petaluma, California. The selection of mix proportions was further adjusted based on a successful HVFA mix design that incorporated two sizes of coarse aggregates (see Table). Batching was done by volume, and the lighter unit weight of the recycled aggregate was significant enough to change the mixture proportions by about 150 lbs/yd^3. The resultant grading of this coarse aggregate blend matched the natural grading of the recycled aggregate very closely so no grading adjustments were made to the recycled aggregate.

Final Mixture Proportions	NAC	RAC
Cement Content lb/yd^3 (kg/m^3)	330 (196)	330 (196)
Fly Ash Content lb/yd^3 (kg/m^3)	330 (196)	330 (196)
Coarse Aggregate 1" lb/yd^3 (kg/m^3)	1309 (7760)	1734 (1028)
Coarse Aggregate 3/8" lb/yd^3 (kg/m^3)	581 (345)	0
Fine Aggregate lb/yd^3 (kg/m^3)	1201 (712)	1201 (712)
Actual Water/Cementitious Ratio	0.36	0.36
Mid-range Water Reducer oz/cwt	10	10

Due to the unpredictable nature of the absorptive capacity of the recylced aggregate, the aggregate was presoaked for 24 hours and allowed to dry to SSD conditions in preparation for mixing. Previous research has determined that this contributes to better workability in RAC mixes[19].

A natural river sand with a fineness modulus of 2.99 and two sizes (1" x #4 and a 3/8" x #8) of natural crushed coarse aggregates with bulk specific gravity (SSD) of 2.70 were used in the natural aggregate concrete (NAC). The same river sand was used in the recycled aggregate concrete (RAC).



Fly Ash, Cement and Admixtures:

A Class F fly ash with a 26% retained on 325 mesh, specific gravity of 2.11 and loss on iginition of 0.33% was used throughout the experiment. The fly ash contained 61.25% silica, 24.15% aluminum oxide and 5.15% ferric oxide; available alkalies comprised 0.63%. A Type II (low alkali) Portland cement was used throughout the experiment along with a medium-range water reducer to enhance workability.

Fresh Concrete Properties

The properties of fresh concrete were very similar for both the control and experimental mixture, and did not differ significantly amongst the two batches made for each mixture. Consistency and cohesiveness were excellent in all cases and slump ranged from 3.5 to 4" for all four batches. Table 4 summarizes the results. The most significant difference between the two mixtures is the reduced unit weight of the RAC which is due to the amount of attached mortar.

	NAC	RAC
Slump, inches (cm)	4 (10.2)	4.25 (10.8)
Unit Weight lb/yd^3 (kg/m^3)	150 (89)	138 (82)
Air Content, %	2	2
Initial Setting Time hours:minutes	6:11	6:38
Temperature, °F (°C)	60 (16)	60 (16)

Casting and Curing

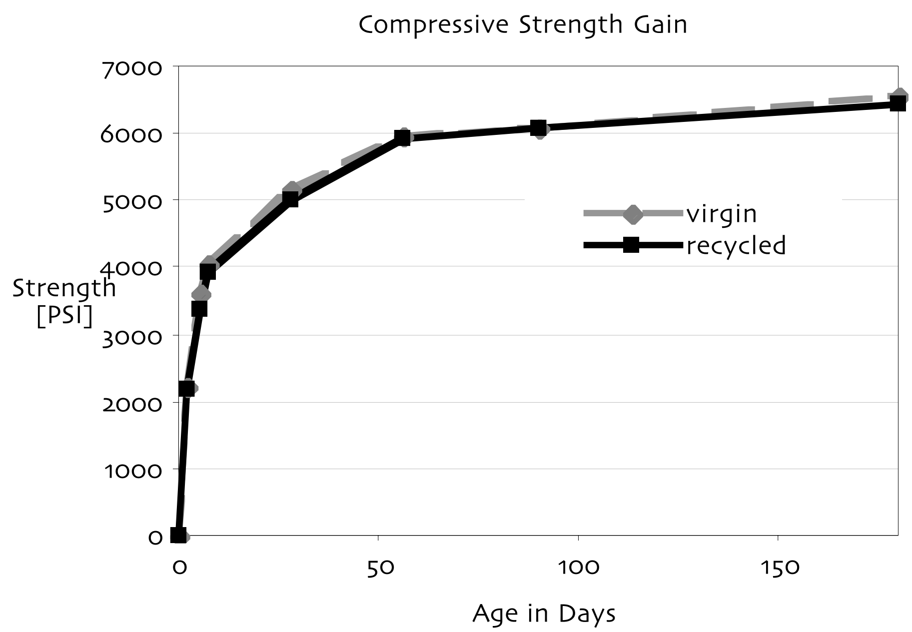
Plastic molded 4" x 8" cylinders were cast according to ASTM Standards using the rodding method of compaction. Cylinders were demolded after 48 hours and water cured for 14 days. From then on cylinders were moist cured.

Properties of Hardened Concrete

Compressive Strength

Compressive strength was determined according to ASTM C 39 at 2, 5, 7, 28, 56, 90 and 180 days. Figure 6 shows the compressive strength gain for both mixtures.

The strength gain for both mixes is very similar. The maximum difference between the NAC and RAC is 2.5% at 28-days, while later ages show a negligible difference between the two. This differs significantly from many published results that indicate a need to increase cementitious content (or reduce the amount of water) in order to create an RAC with similar strength as an NAC[20]. The observed difference could be attributed to an improvement in the bonding surface between the crushed concrete aggregate and the new cement paste due to the high-volume fly ash system.



Tensile Strength

Splitting tensile strength was determined according to ASTM C 496 at 28, 56, 90 and 180 days. On average, the tensile strength of the RAC was 8.8% of it's compressive strength, while that of the NAC was 9.3% of it's compressive strength.

A visual analysis of the fractured surfaces of the tension specimens reveal a significantly higher ratio of fractured aggregates to pulled-out aggregates in the RAC specimens compared to the NAC specimens. In general the RAC specimens fractured through all three phases of the concrete: the new mortar, the old mortar and the aggregates. This is in contradiction with results reported by Kawamura and Torii[21] who noticed that most of the fractures occurred within the cement mortar portion of the recycled aggregates. This reveals that the original concrete strength of the recycled aggregate is very good, and may also point to the existence of deformations within the old aggregates due to use, demolition or repeated crushing.

Elastic Modulus and Drying Shrinkage

The elastic modulus of the NAC and RAC mixtures was determined at 28, 90 and 180 days according to ASTM C 469. At 28 and 90 days, the RAC elastic modulus is 80% of the NAC modulus. At 180 days the RAC modulus in 89% of the NAC modulus. The reduction in elastic modulus is expected due to the reduced stiffness of the recycled aggregate which is approximately 20% old mortar by weight. Thus although the natural aggregate and the recycled aggregate occupied the same volume, the RAC contains only 33% of coarse aggregate by weight while the NAC contains 41.5%. This shows that a significant portion of the recycled aggregate volume is made up of mortar. Perhaps if the recycled aggregate is batched taking into account the attached mortar the elastic modulus would increase, though workability may prohibit this.

Shrinkage of the RAC mixture was 50% higher than that of the NAC at later ages, and even more than that at earlier ages. A higher drying shrinkage is expected due to the decreased modulus of elasticity of the recycled aggregate concrete.

IV. Standards and Specifications

One of the major issues preventing the use of recycled aggregate in structural concrete is quality control. The governing standards and specifications do not provide limits on impurities likely to be found in demolished concrete.

ASTM Specifications

Current ASTM Standard C 33 governs the suitability of aggregates for concrete and has included "crushed hydraulic-cement concrete" since 1982. The 1999 Standard has the following note:

> *"Although crushed hydraulic-cement concrete has been used as an aggregate with reported satisfactory results, its use may require some additional precautions. Mixing water requirements may be increased because of the harshness of the aggregate. Partially deteriorated concrete, used as aggregate, may reduce freeze-thaw resistance, affect air void properties or degrade during handling, mixing or placing. Crushed concrete may have constituents that would be susceptible to alkali-aggregate reactivity or sulfate attack in the new concrete or may bring sulfates, chlorides, or organic material to the new concrete in its pore structure."*

The standard also includes a table of maximum allowable percentages of deleterious substances and physical property requirements for coarse aggregates. A visual inspection of the aggregates revealed that there was less than 2% of unwanted materials, typically a combination of brick, asphalt, metal, glass, and wood. The ASTM table only addresses the contamination of aggregates by "clay lumps and other friable particles", "chert", "coal and lignite" and "material finer than no. 200 sieve". Sieve analysis, after washing of the aggregates, revealed that less than 1% was retained on a no. 200 sieve. The remaining properties of sulfate soundness and abrasion loss were not determined for the experimental sample. This information would ideally be supplied by the aggregate supplier, and the ASTM Standard would be revised to include limits on other contaminants for aggregate from demolished concrete.

ACI Manual of Concrete Practice 221R, Section 6.5

The ACI statement is encouraging since it recognizes the benefits of using recycled aggregate but it is also mainly concerned with quality:

> "*…use is very desirable both economically and environmentally, but great caution must be used… Building rubble may contain deleterious amounts of brick, glass, and gypsum, and any recycled concrete may contain reactive or poor quality aggregates or high chloride contents.*"

The US authorities need to publish more specific quality control guidelines for the suitability of recycled aggregate in concrete. Since there is little published research on the topic it appears that this is an area which could use significant research effort. As it now stands, the use of recycled aggregate in concrete is encouraged but cautioned, which implies that any potential aggregate source would need to undergo fairly extensive testing. This may be prohibitively expensive for some suppliers, especially when the source is continuously changing. The research summarized above demonstrate that a satisfactory quality aggregate can be produced from building demolitions.

V. Conclusion and Recommendations

The engineering properties of recycled aggregate concrete are not significantly different than those of natural aggregate with regard to compressive and tensile strength. The elastic modulus is between 10 and 20% lower and the shrinkage is about 50% more. The presence of old mortar and the subsequent decrease in actual aggregate content of the RAC mixture is responsible for these differences. Fresh concrete properties are not significantly affected by the use of recycled aggregates.

Results from this testing program do not agree with much of the available literature with respect to the strength, workability and water requirement of the RAC compared to the NAC. The conclusions based on hundreds of tests are that strength is reduced by at least 10%, workability is reduced and water requirement is increased by at least 5%. The discrepancies discovered in the above described mixture are likely due to the incorporation of fly ash and the use of a good quality recycled aggregate. This experimental program should be repeated and expanded to verify these results and explore the use of non pre-soaked aggregates to ease production and the incorporation of higher volumes of recycled aggregate to offset elastic modulus reductions.

The reuse and recycling of waste products is an essential step towards the development of a sustainable future. Considering the magnitude of the construction industry's impact on natural resource use and solid waste production it is imperative that alternatives to virgin materials be explored and incorporated into the building process. With currently available materials in the San Francisco Bay Area it is feasible to produce sustainable concrete, using recycled concrete aggregate in a high-volume fly ash system, which achieves satisfactory mechanical performance. By utilizing crushed concrete and other demolition wastes we can begin to close the natural resource loop of the construction industry, something that the future depends on.

For a more detailed version of this paper please contact sue.costabile@arup.com for an electronic version.

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