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Recycled Materials in Portland Cement Concrete

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16. Abstract

This report pertains to a comprehensive study involving the use of recycled materials in Portland cement concrete. Three different materials were studied including crushed glass (CG), street sweepings (SS), and recycled concrete (RC). Blast furnace slag was also considered as a cementitious additive for enhancing the durability characteristics of the mixture. This research was performed and completed earlier. Four reports were submitted covering literature survey, mix details and experimental results for the recycled materials in the study. However, in these studies, the NJDOT class A concrete was substantially modified in order to establish an optimize mixture. The optimized mixture was used in conjunction with the recycled materials. This was done due to the fact that the researchers were aware of the deleterious effects of the recycled constituents on the Class A mix. However, NJDOT project engineers indicated that despite the outcome, they would like the experiments to also encompass standard class A concrete in conjunction with the recycled materials. The project was extended at no additional cost and a second series of experiments were performed with mixtures that included class A concrete as a base material. The bulk of this report pertains to these results. The research phase corresponding to class A mixtures is designated as Phase-A, and the earlier research with optimized proportions corresponds to Phase-B. Representative results from the earlier study (Phase B) for the crushed glass and recycled concrete are also given for completeness.

Based on the results of this study, it is recommended that street sweepings shall not be used with any type of concrete mixture due to its variability. Crushed glass and recycled aggregate concrete shall be used with optimized cementitious mixtures and not standard class A concrete. These recommendations are mainly based on the decreased durability attributes of such materials. Even with the optimized cementitious mixtures, the reduction in compressive strength as a function of curing age for crushed glass concrete points at uncertainty regarding the long term load bearing characteristics of such material. It is recommended that the crushed glass concrete not be used in structural and load bearing applications. Recycled concrete can be used for secondary applications and it possesses enhanced durability attributes in optimized, cementitious mixtures.

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TABLE OF CONTENTS

ABSTRACT 1
Wastes and By-Products for Use in Portland Cement Concrete 2
RESEARCH OBJECTIVES 3
LITERATURE SURVEY 3
Silica Fume 3
Blast Furnace Slag 4
Fly Ash 6
Recycled Concrete 7
Crushed Glass 8
Street Sweepings 9
Crumb Rubber 10
Plastics 10
Ceramic 11
Sawdust 11
Recycled Materials Used in New Jersey Highways 12
LABORATORY TESTS 13
Compressive and Flexure Strength 13
Permeability 13
Accelerated Mortar Bar Test 14
Test Method 14
Test Procedure 14
EXPERIMENTAL PROGRAM 15
PHASE A – NJDOT CLASS-A MIXTURES 16
Phase-A Experimental Results 20
Discussion of Phase-A Results and Recommendations 20
PHASE B – OPTIMIZED MIXTURES 22
Crushed Glass Concrete 23
Recycled Aggregate Concrete 29
CONCLUSIONS 31
REFERENCES CITED 32

LIST OF FIGURES

Figure 1. Change in compressive strength as a function of age for 5% CGC.
Figure 2. Change in compressive strength as a function of age for 10% CGC.
Figure 3. Change in compressive strength as a function of age for 15% CGC.
Figure 4. Change in compressive strength as a function of age for 100 % CGC.
Figure 5. Comparison of 28-day strengths for all the CGC concretes.
Figure 6. Comparison of the 28-day strength for concretes with various percentages of RCA as coarse aggregate.

LIST OF TABLES

Table I. Mix Proportions for typical NJDOT class A concrete
Table 2. Mix Type Designations and Descriptions.
Table 3. Typical laboratory batch proportions for type 1 mix.
Table 4. Typical laboratory batch proportions for type 2 mix.
Table 5. Typical laboratory batch proportions for type 3 mix.
Table 6. Typical laboratory batch proportions for type 4 mix.
Table 7. Typical laboratory batch proportions for type 5 mix.
Table 8. Typical laboratory batch proportions for type 6 mix.
Table 9. Typical laboratory batch proportions for type 7 mix.
Table 10. Compressive strength data.
Table 11. ASR test results in terms of mortar bar expansions
Table 12. Chloride Ion Permeability test results in terms of Charge Passed.
Table 13. Mix Proportions for Crushed Glass Aggregate Concrete
Table 14. CGC Compressive and Flexural (Modulus of Rupture) Strength Test Results.
Table 15. Permeability Test Results for CGC
Table 16. ASR test results for CGC concrete.
Table 17. RCA mix design.
Table 18. Permeability Test Result
Table 19. Compressive Strength and Modulus of Rupture for RCA concrete.

ABSTRACT

This report pertains to a comprehensive study involving the use of recycled materials in Portland cement concrete. Three different materials were studied including crushed glass (CG), street sweepings (SS), and recycled concrete (RC). Blast furnace slag was also considered as a cementitious additive for enhancing the durability characteristics of the mixture. This research was performed and completed earlier. Four reports were submitted covering literature survey, mix details and experimental results for the recycled materials in the study. However, in these studies, the NJDOT class A concrete was substantially modified in order to establish an optimized mixture. The optimized mixture was used in conjunction with the recycled materials.

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INTRODUCTION

Increasing waste volumes and escalating disposal costs have forced a reassessment of public attitudes regarding the way society handles its wastes. This expanding awareness has given rise to a definite trend toward recycling or use of a wide variety of solid waste materials. New Jersey by virtue of being one of the highly industrialized, and densely populated states in the nation was one of the first to encounter the waste management problems in the 1970s. Many of the state disposal facilities reached their intended capacities, and much of New Jersey's waste material was shipped to landfills in the adjacent states. The legislative body was forced to mandate recycling of waste material in order to remedy the problem. In the 1990's, motivated by a recognition of the resource value in high volumes of formerly discarded materials such as scrap tires, paving rubble, combustion by products, and mining wastes, waste recycling in has advanced from simple newspaper drives to a large industry, Reusing such materials reduces disposal volumes and costs, conserves natural resources, and may even generate revenue. Because highways require huge volumes of construction materials, highway agencies have become frequent participants in efforts to recycle or reuse diverse waste materials.

Solid waste materials differ vastly in their types and characteristics as well as in the applications for which they may be suited. Experiences with using waste materials in highways can vary considerably, depending on climatic differences, compositional fluctuations, material handling techniques, and construction procedures. Some waste materials and byproducts (such as reclaimed paving materials, slags, and fly ash) have been used beneficially in the highway system for many years. Other materials have very little performance history from which to evaluate their potential for sustained use in highway construction. A number of waste materials may be suitable for use in constructing highways, but may have other, more economical or productive uses.

Besides these considerations, the level of practice and knowledge of waste material use in highway construction varies from state to state. NJDOT engineers and decision makers need to be aware of the various types of waste materials, how or if they can be used in highway construction, experiences of others in using such materials, and their technical, economic, and environmental considerations.

Wastes and By-Products for Use in Portland Cement Concrete

Solid wastes and by-products for general highway usage are classified according to source in one of four general categories:

- Agricultural,
- Domestic,
- Industrial, or
- Mineral.

In reference to Portland cement concrete (PCC), current practice involves two types of recycled materials that have been used effectively for production of concrete: by-products of other industries, and waste concrete itself. Research and development activities pertaining to the use of mineral, and industrial by-products in Portland cement concrete are too numerous to fully describe here. Usage of minerals in Portland cement concrete depends on the required attributes. For instance, some mineral admixtures are used in conjunction with PCC due to their pozzolanic properties (e.g., low -calcium fly ash), some due to cementitious attributes (e.g., granulated iron blast-furnace slag), whereas others are both cementitious and pozzolanic (e.g., high-calcium fly ash). It is important to note that the mineralogical compositions and particle characteristics of these by-products rather than their chemical composition or the source of material affect the behavior of Portland cement concrete.

RESEARCH OBJECTIVES

The main goal of the research reported here was to investigate the suitability of using recycled glass, recycled concrete, and street sweepings with NJDOT class –A concrete mixtures. Series of experiments needed to be performed in order to investigate the mechanical properties and durability characteristics of the concrete containing recycled constituents. The use of Ground Blast Furnace Slag (GBFS) was also investigated as a stand-alone additive as well as in conjunction with other recycled materials in order to examine the feasibility of its use with NJDOT concrete mixtures.

The research presented here is divided into two distinct sections outlined in the following:

1. Recycled materials in NJDOT class –A Portland cement Concrete mixtures.
2. Recycled materials in optimized Portland Cement Concrete mixtures.

Early on in the project, it was understood that the recycled glass and street sweepings would have detrimental effects on class-A concrete. Despite this knowledge, the experimental program included determination of the effects of the recycled materials on the mechanical characteristics and durability of standard class-A mixes. Optimized mixtures were then developed and tested in order to examine their suitability for NJDOT projects. In the design of optimized mixtures advantage was taken of mineral admixtures and both silica fume (SF) and GBFS were employed for durability enhancement of the mixtures. An extensive survey of literature preceded the experimental work.

LITERATURE SURVEY

The survey of literature given here includes the recycled materials used in this study as well as other types of materials. Each material is discussed separately for clarity. The literature included here is not exhaustive, yet it pertains to more specific applications corresponding to

Silica Fume

Silica fume, which is used as a partial replacement for Portland cement, has proved to be a useful recycled material admixture in concrete. Silica fume is a by-product of the reduction of high purity quartz with coal or coke and wood chips in an electric arc furnace during the production of silicon metal of ferrosilicon alloys. Silica fume, which condenses from the gases escaping from the furnace, has a very high content of amorphous silicon dioxide and consists of very fine spherical particles. The result from silica fume variability studies for chemical composition and physical properties indicates that silica fume uniformity from a single source is reasonably similar to the uniformity associated with ground granulated blast furnace slags. The variations are smaller than those associated with fly ashes. Currently, the relationship between variations in physical and chemical properties of silica fume and performance in concrete is not well established.

Mortar bar expansion test results with various silica fume contents indicate that expansions were reduced with increasing replacements by silica fume. A 10% by volume silica fume replacement meets the ASTM C618 Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use as a Mineral Admixture in Portland Cement Concrete expansion limit of 0.02% at 14 days. By the ASTM C33 Concrete Aggregates and C227 Potential Alkali Reactivity of Cement-Aggregate Combinations (Mortar-Bar Method) maximum mortar bar expansion limit of 0.1%, 10% silica fume should be adequate. Therefore, it appears that silica fume may be effective in reducing deleterious alkali silica expansions. The job-specific combinations of cement, silica fume, and aggregate should be evaluated before silica fume is recommended for use. Silica fume effects on properties of fresh concrete are primarily the reduction in bleeding, the increase in cohesiveness and a lesser tendency toward segregation than concrete without silica fume. On the other hand, the use of silica fume will not significantly change the unit weight of concrete and increase the potential for plastic shrinkage cracking.

Effects of silica fume on properties of hardened concrete provide low permeability characteristics of concrete and improvements in long-term durability. Test results which contain 10 to 20 percent by mass replacement with silica fume incorporated in the proprietary admixture have good mechanical properties, where it can develop higher early compressive strengths hold for 28 day. In the long term, observation has shown that there is little or no increase in strength. Flexural strength is improved when silica fume is introduced to concrete. The splitting tensile strength is not improved for the silica fume mixes. The elastic modulus is approximately equal to the Portland cement concrete at 28 days. Specific gravity of silica fume has a range of 2.1 to 2.2. Bulk unit weight has a range of 340 to 670 lb/yd^3 (573 to 1130 kg/m^3).

Blast Furnace Slag

The use of iron furnace slag as a constituent of concrete, either as an aggregate or as a cementing material, or both, is well known. Research has suggested that, in general, hydration of Ground Granulated Blast Furnace (GGBF) slag in combination with Portland cement at normal temperature is a two stage reaction . Initially, the predominant reaction is with alkali hydroxide, subsequent reaction is predominately with calcium hydroxide. Use of GGBF slag as a partial replacement for Portland cement, is known to reduce the potential expansion of concrete due to Alkali-Silica Reactivity (ASR). When slag contents are used in percentages ranging from 40 to 65 percent of total cementitious material, expansion is virtually eliminated when tested in accordance with ASTM C227 Potential Alkali Reactivity of Cement-Aggregate Combinations

(Mortar-Bar Method). Compared to low-calcium fly ash, which does not usually make a significant contribution to the strength of Portland cement concrete until reaching the fourth week of hydration, the strength contribution by granulated iron blast-furnace slag is exhibited as early as 7 days after hydration. Many researches have indicated that slag particles of less than 10 μm add to early strengths in concrete up to 28 days; particles of 10 to 45 μm contribute to subsequent strengths, whereas particles coarser than 45 μm are arduous to hydrate.

In most cases, GGBF slags have been used in proportions of 25 to 70 percent by mass of the total cementitious material. The proportion of GGBF slag should be dictated by the purposes for which the concrete is to be used, the curing temperature, and the grade of GGBF slag. There appears to be an optimum blend of GGBF slag that produces the greatest strength at 28 days as tested by ASTM C109 Compressive Strength of Hydraulic Cement Mortars. This optimum is usually found to be 50% of the total cementitious material, although this relationship varies depending on the grade of GGBF slag. Due to the high proportions of GGBF slag commonly used, allowances should be made for changes in solid volume due to the difference in specific gravity of slags and Portland cement. Due to the greater solid volume and the higher fineness of GGBF slag, more coarse aggregate may be used without a loss of workability. GGBF slags are usually substituted for Portland cement on a one-to-one basis by mass and always considered in the determination of the water-cementitious material ratio. Effects of chemical admixtures on the properties of concrete containing GGBF slags are similar to those for concrete made with Portland cement as the only cement. In all cases, the placeability of the concrete containing 50% GGBF slag was superior to that of mixtures without GGBF slag. Increased slump was obtained with all GGBF slag blends tested when compared to concrete without GGBF slag at the same water content. When the GGBF slag is finer than the Portland cement and is substituted on an equal-mass basis, bleeding of concrete is reduced. When the GGBF slag is coarser, the rate and amount of bleeding may increase.

Compressive and flexural strength-gain characteristics of concrete containing GGBF slag can vary over a wide range. When compared to Portland cement concrete, use of Grade 120 slag typically imparts reduced strength at early ages (1 to 3 days) and increased strength at later ages (7 days and beyond). Other grades tend to impart reduced strength at all ages.

When highly active GGBF slag was tested, the greatest 28-day strengths are found with blends of 40 to 50 percent. The same modulus of elasticity of concrete containing blast furnace slag cement was found as concrete with Type I cement. Many studies were made in resistance to freezing and thawing and to deicing chemicals. When concrete made with blast furnace slag cement was tested in comparison with Type I and Type II cements, their resistance to freezing and thawing in water and their reduced permeability of concrete were essentially the same.

ASTM C989 Ground Granulated Blast-Furnace Slag for Use in Concrete and Mortars provides for three strength grades of GGBF slag, depending on their respective mortar strengths when blended with an equal mass of Portland cement. The classifications are Grades 120, 100 and 80.

Specific gravity of blast furnace slag has a range of 2.85 to 2.94. Bulk unit weight has a range of 1680 to 2020 lb/yd^3 (2831 to 3404 kg/m^3).

Fly Ash

Fly ash from coal-burning power plants is used in concrete primarily because of its pozzolanic and cementitious properties. These properties contribute to strength gain and improved durability when used with Portland cement. Other principal reasons for using fly ash include economy and beneficial modification of certain properties of fresh and hardened Portland cement concrete.

Fly ash use in concrete generally causes an increase in setting time both initial and final set. It normally allows a reduction in the quantity of water in a concrete mixture necessary to produce a target slump. Because of the fineness and rounded shape of the fly ash particles, its use generally improves the cohesion and workability of the concrete at a given slump. As the concrete hardens, the fly ash makes use of developed heat from portland cement hydration to accelerate pozzolanic reactions and, thereby, promotes the reaction of the fly ash with available calcium and alkali hydroxides. The principal variance between fly ash aggregate and other lightweight aggregate is the excess requirement of air entraining agent when introducing fly ash aggregate. The fine portion of the fly ash aggregate may also be poorly graded, with the outcome that concrete mixes prepared with unmodified aggregate may be tough to work with. Therefore, it may be advantageous to substitute a part of the fines with normal weight sand. In order for the concrete produced to behave similarly to other lightweight concretes in unit weight, compressive and tensile strength, modulus of elasticity, drying shrinkage, creep and freeze-thaw resistance, enough normal weight sand is desirable to be included to make a workable mix

Fly ash is divided into Class F and Class C. Class F is a low calcium fly ash that contain a large proportion of silicate glass of high silica content plus crystalline phases of low reactivity, typically mullet, magnetite and quartz. Class C is an active compound in addition to calcium alumna-silicate glass. The strength related properties of concrete containing Class C fly ash, as compared to Class F fly ash, are influenced by the cementitious calcium alumna-silicate glass. For optimum economy, Class F fly ash is normally used at the rate of 15 to 20% of total cementitious material, and Class C fly ash is normally used in the range of 15 to 35% .

The shape, fineness (it has a significant influence on its performance in concrete), particle-size distribution, density, and composition of fly ash particles influence the properties of freshly mixed, unhardened concrete and the strength development of hardened concrete as previously indicated. Fly ash color and the amount used can influence the color of the resulting hardened concrete. The absolute volume of cement plus fly ash normally exceeds that of cement in similar non-fly ash concrete mixtures. Increased long term strength through continued pozzolanic reaction is achieved with most fly ashes in concrete. Early strength development can generally be compensated for by proper proportioning of the mixture. Class C fly ashes typically give very good strength results at 28 days. The modulus of elasticity of fly ash concrete, as well as its compressive strength, is somewhat lower at early ages and a little higher at later ages than similar concrete without fly ash. The effects of fly ash on modulus of elasticity is not as significant as the effect of fly ash on strength. When compared for Class F and Class C, fly ash found no significant difference in the resistance to freezing and thawing of concrete with and without fly ash. Permeability is reduced after using fly ash. The use of adequate amounts of some fly ashes can reduce the amount of aggregate reaction and reduce or eliminate harmful expansion of concrete due to sulfate attack, steel corrosion, and ASR. Where the addition of fly ash increases the paste volume, drying shrinkage may be increased slightly if the water content remains constant. If there is a water-content reduction, shrinkage should be about the same as concrete without fly ash.

Specific gravity of fly ash is about 2.1~2.8. Bulk unit weight has a range of 1510 to 1680 lb/yd^3 (2544 to 2831 kg/m^3).

Recycled Concrete

The activities of renovation and demolition in the maintenance and modernization of buildings generate large amounts of solid waste and rubble, adding to the already vast and continuously increasing solid waste stream. Currently, there is a widespread move to adopt new operational strategies aimed at prevention and minimization of the waste generation as close as possible to the sources aiming for a responsible pursuit of environmentally sustainable developments. This development is primarily induced by aspects of economics such as rising tip charges, transport distances and fuel costs, which are forcing demolition contractors to find other less costly options to dispose of building and demolition waste than at waste management centers and landfill sites. The use of recycled concrete aggregate (RCA) as an alternate for dense-graded aggregate base course (DGABC) applications over the recent years have been approximately 10% to 15%. Most of the contractors are left with the decision as to which material to be used where their usage of RCA is seemingly based on cost. The aggregate particles of recycled concrete compare well to conventional mineral aggregates in that they possess good particle shape, high absorption, and low specific gravity. Recycled concrete aggregate has also been shown to have no significant effect on the volume response of specimens to temperature and moisture effects. However, the presence of gypsum in concrete rubble, which is used as aggregate for new concrete, can produce an expansive reaction with the cement matrix due to the concentration of sulfate ions. Similarly, chlorides from deicing salts may interfere with the action of admixtures in new concrete, and causes changes in setting behavior. Nevertheless, these contaminants do not pose serious problems since most of the contaminants can be removed by washing and density separation techniques. Questions were asked regarding the quality of recycled concrete aggregate, cost-effectiveness of the material, economical steel removal techniques, proper proportioning of concrete mixtures using reclaimed coarse and fine aggregates, and the degree of strengths which could be obtained. During breaking up an old concrete and reusing it as aggregate, the cost of recycled concrete is mainly the cost of crushing. Reclaimed fines are used as a replacement for normal fine aggregate. It is recommended that the reclaimed fines be used at a maximum of 30% of the total fines used in the mixture. RCA are usually crushed, classified and recombined to meet the same gradation requirements for virgin DGABC. The quality requirements have to be the same as those apply to DGABC, with the exemption of allowing up to 10% asphalt concrete in the material. A recent study (Bairagi, Ravande and Pareek, 1993) concludes that "up to 50% of natural aggregate could be replaced by recycled aggregate without seriously affecting the properties of the concrete, both in the fresh and hardened states". According to the American Concrete Pavement Association (ACPA), only 10~20% replacement of fine aggregate usually is acceptable in a concrete mixture. Recycled concrete aggregate is being used more than ever before. Portland Cement Concrete (PCC) aggregate is being used to some degree on almost all pavement projects. Crushed concrete has been successfully used as subbase and base course materials and in bituminous mixes in some projects. Recycled concrete aggregate (RCA) has been used in base binder courses. Because of the non-homogeneous nature of recycled concrete, it does not meet strict DOT specifications for quality. Generally, concrete made with recycled aggregate is economically feasible where disposal problems exist or where natural aggregates are scarce and where transportation costs of natural aggregates can offset the cost of crushing the concrete.

The density of concrete made with recycled concrete aggregate shows opposite properties with the normal one. Its density is less than normal concrete. It has been found that the workability of recycled concrete is low. In concrete produced using recycled coarse concrete aggregate, compressive strength, tensile strength and modulus of elasticity are decreased by about 15-25%. The damping capacity is increased up to 30%. This strength reduction can be compensated by using pozzolans such as fly ash and silica fume. Frost resistance of recycled concrete has been proven not to differ much from that of the conventional concrete. Concrete mixtures which incorporate recycled concrete aggregate feature good freeze-thaw durability characteristics. With the increase of recycled concrete aggregate amount in mixture, the values of toughness, plastic energy capacity and elastic energy capacity decreases.

Specific gravity of recycled concrete aggregate is 2.4~2.5, bulk loose dry density 700~1000 lb/yd^3 (1180 to 1685 kg/m^3), 30-minute water absorption 1.5~7% .

Crushed Glass

Over the last few years considerable progress has been made in the development of new building materials from waste glass. There are innumerable environmental reasons why sustained efforts should be made to reduce the amount of glass in the solid waste stream. Unlike other forms of waste, such as paper and organic constituents of garbage, it does not decompose when dumped on the land and constitutes a high proportion of incinerator residue. Studies have indicated that cost savings will be seen in reduced expenses for glass transport to distant landfills. In the U.S.A, several promising new products based on scrap glass are currently in use by the trade. The first and most important is the so-called building panel made of glass combined with pieces of brick or concrete and fused by heat to create construct-units with high load bearing properties. Glass-rubble building panels possess excellent crushing strength, low water absorption and the ability to withstand extremes of temperature without signs of deterioration. Crush glass aggregate should pass the $^3/_4$- or $^3/_8$-inch (19 or 9.5 mm) sieve depending on the effect desired. Crushed glass is relatively little and limited in the concrete application as aggregate. Some comparisons have been made on the effect of replacing a normal aggregate with crushed glass obtained from broken bottles. In one mix, the normal weight fine aggregate was replaced by glass of the same size, in another the coarse aggregate was replaced by coarse glass and in another, both were replaced. Starting with an 8000 psi (55120 kPa) concrete mix of normal weight fine aggregate and gravel the strength was reduced to less than 50 percent of the original when the fine aggregate was replaced, to less than 40 percent of the original when the coarse aggregate was replaced and to less than 30 percent when both were replaced. The resistance to salt scaling in freezing tests was also reduced in the same way. But crushed glass is said to have produced satisfactory strength in pressed concrete brick. It may also mean that the strength achieved with fine glass aggregate was adequate.

One of the main constituent of glass is silica. Studies have indicated that the deleterious expansion is caused even with a low alkali cement, so it is of great importance to pay attention to ASR in the concrete mix which involves crushed glass aggregate. The measure to prevent ASR were designed to avoid sufficient alkalis, sufficient moisture, and aggregates with reactive silica from occurring simultaneously in concrete. If the concrete is to be exposed to moisture in service, aggregates classified as deleteriously reactive either a low-alkali Portland cement or a Portland cement-pozzolan combination that would be effective in preventing ASR deterioration.

Before using any glass as an aggregate, assurance should be obtained from the supplier that it will meet the requirements of ASTM C33 with respect to ASR by performing mortar bar test, according to C227. In many cases it may be sufficient simply to use low alkali cement (alkali content is below 0.6 percent), but this should be based on Laboratory evidence. On the other hand, any glass aggregate to be used in concrete must certainly be required to meet the ASTM requirements just cited, either by itself or in combination with some other material. So far, crushed glass appears to be valuable for use in exposed aggregate concrete when rightly used.

Street Sweepings

Types of waste materials found on roadway include street sweepings, storm sewer clean out materials and other similar road wastes. The type and amount of contaminants present in road wastes puts them in one of the three categories: 1) road wastes that contain hazardous waste, 2) road wastes as non-hazardous ID 10 municipal solid waste, or 3) road wastes that contain contaminants below regulatory concern [100]. New Jersey Department of Environmental Protection (NJDEP) describes a number of different types of potential uses for road wastes among them, fill for potholes, embankment for emergency road repairs, containment/absorption medium for hazardous materials spill response, sub-base fill, deicing/anti-skid material, landfill cover, recycling centers, and soil mix additive for pavement materials. Street sweepings may be used directly as additives in materials such as concrete or asphalt for paving or other uses, without prior approval by NJDEP, provided that they are not contaminated. Street sweepings in their present form may be considered as very fine aggregates. The test will decide if they can be used as replacement materials for natural fine aggregates in concrete.

Crumb Rubber

The tire rubber has been used in hot-mix asphalt and portland cement concrete. Some researchers examine strength and toughness properties of concrete in which different amounts of rubber-tire particles of several size were used as aggregate. The concrete mixtures exhibited lower compressive and splitting-tensile strength than did normal concrete. However, these mixtures did not demonstrate brittle failure, but rather a ductile, plastic failure, and had the ability to absorb a large amount of plastic energy under compressive and tensile loads.

Plastics

Recycled plastics can be used as some replacement of aggregate in concrete. Addition of recycled plastics to lightweight concrete can help overcome problems with the brittleness and relatively high unit weight of concrete, and also it can help reduce and control drying shrinkage cracks. The statistics of the test indicated:

a) Recycled plastics at 7.5 to 15 percent volume fractions gave comparable flexural strengths to that of a control concrete mix. Flexural toughness was 4.5 to 8 times higher than the control concrete mix.
b) Concrete is fairly strong in compression, and failure in compression rarely occurs.
c) Recycled plastics have a significant and positive effect on the impact resistance of concrete beyond the initial crack up to failure.
d) Permeability is reduced generally compared with normal concrete.

Ceramic

Crushed tile has been used as an alternative coarse aggregate in concrete. Based on series of conducted tests and investigations, the followings summarize the results obtained:

a) Average bulk and specific gravity of crushed tile decrease 30% and 11%, individually, than normal weight crushed stone aggregate.
b) Crushed tile compared to crushed stone was about 37% lighter and fell on the upper limit of light weight aggregate.
c) Abrasion loss of crushed tiles was about 39% greater than that of crushed stone aggregate.

The ratio of compressive, tensile, and flexural average strengths of crushed tile concrete at 28 days relative to normal concrete were 1.02, 1.7, and 1.29, respectively. Total substitution of crushed tile for crushed stone as coarse aggregate produced a concrete with tensile and flexural strengths higher and compressive strength lower than the 50% volume substitution at 28 days. The compressive stress-strain curve of crushed tile concrete was close to that of crushed stone concrete with normal strength.

Sawdust

Sawdust has been used in concrete for at least 30 years, but not widely. Although seriously limited by its low compressive strength, sawdust concrete can be made to perform well in certain floor and wall applications. Dry sawdust concrete weighs only 30% as much as normal weight concrete, and its insulating properties approximate those of wood. It can be sawed and drilled as wood and it will hold nails and screws. With proper cement to sawdust ratios, it is not flammable. As a basic construction material, sawdust concrete does indeed have its functions. It performs well in a limited number of floor applications or as a building component not subject to high structural stresses. It has serious limitations that must be understood before it is put to use. Within these limitations, the advantages that sawdust concrete offers -- lightness of weight, sawability, nailability and low thermal conductivity -- make it a useful construction material. However, the strength of sawdust concrete when made in the most commonly used proportion of 1:3 is only 10 to 20 percent of that of normal concrete. It is not usable where high structural strength is required or where it would be subjected to heavy traffic and severe abrasive action. Its wood content also prohibits installation of lean mixes in environments of excessive moisture. Cement to sawdust ratios in standard sawdust concrete mixes are usually from 1:2 to 1:6. However, strength is drastically reduced as the percentage of sawdust is increased.

In general, sawdust concrete is not recommended for use where water accumulates or where water is constantly present.

Recycled Materials Used in New Jersey Highways

Solid recycled materials differ vastly in their types and characteristics as well as in the applications for which they may be suited. Experience with using recycled materials in highways can vary considerably, depending on climatic differences, compositional fluctuations, material handling techniques, and construction procedures. Some recycled materials and byproducts, such as reclaimed paving materials, slag and fly ash, have been used beneficially in the highway system for many years. Recycled concrete began being used in highway reconstruction projects in the US in the early 1970s. Lately, more and more States began emphasizing on the use of recycled concrete in pavement reconstruction. Today, the use of recycled concrete in highway projects is becoming a routine in several States. Since highways require huge volumes of construction materials, highway agencies have become frequent participants in efforts to recycle or reuse diverse waste materials. A number of waste materials may be suitable for use in constructing highways, but some may have more economical or productive uses.

The level of practice and knowledge of recycled material used in highway construction varies from State to State. NJDOT engineers and designers need to be aware of the various types of recycled materials on whether they can adopted in highway construction or not, depending heavily on their technical, economic, and environmental considerations. Based on these considerations, NJDOT has been persistently involved in the research and development of recycled materials for highway construction applications. Employment of recycled concrete aggregate as an alternate for dense-graded aggregate base course was based on a successful research and development program. Annual usage of recycled concrete aggregate is approximately 10% to 15% in New Jersey.

NJDOT's experiences with recycled materials include:

- Use of reclaimed asphalt pavement as an alternate in hot mix asphalt in surface, base and binder course mixes.
- Incorporation of fly ash as an additive in portland cement concrete to mitigate potential ASR problems, and improve long term strength.
- Specifications for use of broken container glass in hot mix asphalt.
- Other potential recycled materials to be investigated for usefulness:
- Street sweepings to be used as a partial replacement for fine aggregate in concrete.
- Crushed glass to be used as a partial substitute for coarse aggregate in concrete.
- Usage of some mineral materials will be researched further.

It is obvious that the recycling material accruing should be directly used for economical and ecological reasons. Various test and research show that such aggregate may be universally used. It is important to recognize that recovery and reuse of recycled materials is constantly changing and expanding, especially for construction purposes. New ways are being found to process and make use of discarded materials that were formerly part of the waste stream. Barriers such as cost, industry culture, perceived lack of market, inhibitive specifications, competition and space constraints must be overcome for the success of recycling. In addition to that, many researches and studies are needed to effectively incorporate the new technologies into practice, particularly, in construction application of highways and transportation structures.

LABORATORY TESTS

Laboratory tests were performed in order to determine the mechanical properties and the durability characteristics of the concrete containing recycled materials. The general criteria pertaining to the individual tests performed here are outlined in the following subsections:

Compressive and Flexure Strength

In accordance with ASTM C39 (AASHTO T-22) Compressive Strength of Cylindrical Concrete Specimens, the 4x8-in cylinder were required to perform the uni-axial compressive test in order to obtain the compressive strength and modulus of elasticity. The 4x4x14-in (10.2x10.2x35.6cm) beam were used to determine the flexural strength and to obtain the modulus of rupture, in accordance with ASTM C 78 Flexural Strength of Concrete. To determine the compressive and flexural strengths, cylinders and beams were tested within about 28 days period.

Permeability

Permeability tests were conducted in accordance with ASTM C1202 Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration. The permeability of concrete is an important parameter in determining its durability. Permeability provides a measure of the concrete's physical resistance to the ingress of the destructive agents (carbon dioxide, chlorides, and sulphates) and the movement of oxygen and water, which is required for corrosion. Although there is no single test for estimating the durability of concrete exposed to different (water, ice, salt, etc...) conditions, permeability is commonly considered the best parameter for characterizing the capability of the concrete to resist deterioration. The basic method of permeability test is by mean of measuring the electrical conductance of concrete to evaluate the capacity of concrete resistance to chloride ion penetration. Specimens of permeability test will be sawed from cylinders and cut in 2-in (50.8mm) slice (diagram: 4-in) with the cut parallel to the top of the cylinder. The details of test method, processing, other conditions and final evaluating standard will follow the above ASTM test procedure.

Accelerated Mortar Bar Test

ASTM C1260 Potential Alkali Reactivity of Aggregates, known as accelerated mortar bar method (AMBM), is used as a standard test method for potential alkali reactivity of aggregate. ASTM C1260, which involves immersion of mortar bars in 1N NaOH at 176°F for 16 days. The test method will measure the expansion of mortar bars, made with recycled aggregate at various times during the accelerated mortar tests. The mix proportion of dry materials of mortar bars will use one-part cement to 2.25 parts of graded aggregate by mass. On the other hand, the cementitious specimens that were tested will be crushed and mixed in order to prepare a group of specimen according to the determined proportion in mechanical test. The result of this test will be analyzed with other results of mechanical test obtained previously.

Test Method

All test equipment will be prepared in accordance with ASTM C227, C490 and C1260. The following is a brief list of the equipment required:
Modes: At least five modes are desired. For test specimens, 1 by 1 by 111/4-in (2.5x2.5x28.6cm) prism equipped with a 10-in (25.4cm) length gage is required. Size details and requirement of modes are found in ASTM C490.
Containers: They must be of such a nature that the bars can totally be immersed in 1N NaOH solution and must be made of material that can withstand prolonged exposure to 176°F. The bars in the container must be placed and supported so that the solution has access to the whole of the bar, therefore, it should be ensured that the specimens do not touch the sides of the container or each other. The specimens, if stood upright in the solution, shall not be supported by the metal gage stud. (Some microwave-proof food storage containers made of polypropylene or high-density polyethylene have been found to be acceptable. A covered container that has been recommended by ASTM C227 acceptable for this purpose is sold by the United States Plastic Corp., 1390 Neubrecht Rd., Lima, OH 45801).
Length comparator: Those selected should be equipped with a dial micrometer or other measuring device graduated to read in 0.001 or 0.002-mm units, accurate within 0.002 mm in any 0.02mm range, and within 0.004mm in any 0.2mm range, and sufficient range (at least 8.0) in the measuring device to allow for small variations in the actual length.
Storage oven: In which the specimens will be stored in the containers at a temperature of 176+3.6°F.
Other apparatus: Sieves, Mixer, Paddle, Mixing Bowl, Tamper and Trowel etc.

Test Procedure

Materials shall meet TABLE 6 requirements and mortar bars will be prepared and measured as follow:

1. Mix paste, set the metal gage stud and fill molds afterward with two approximately equal layers, where each layer is compacted with a tamper.

2. Recycled materials in optimized Portland Cement Concrete mixtures.
3. Place mortar bars in their molds in the moist cabinet or room immediately.
4. After 24-hour demolded, make an initial comparatory reading and recording data.
5. Place the specimens in a storage container with sufficient tap water to totally immerse them. Seal and place the containers in an oven at 176°F for another 24 hours.
6. Remove the containers one at a time. Remove other containers only after the bars in the first container have been measured and returned to the oven. Remove the bars one at a time from the water and dry their surface with a towel. Take the zero reading (the reference bar should be read prior to each set of specimens) of each bar immediately after drying, and read as soon as the bar is in position. Complete the process of drying and reading within 15+5 seconds of removing the specimen from water. After readings, leave the specimen on a towel until comparatory readings have been taken on the remainder of the bars.
7. Dilute 1N NaOH solution. Each liter shall contain 40 g of NaOH dissolved in 900 ml of water to obtain 1.0 L of solution. Place all bars in containers to be totally immersed. Seal the container and return it to the oven.
8. The measurements will be continued regularly, at approximately the same time each day from day 1 to 14 days. Readings will continue beyond 14 days period, take at one reading per week until 48 days. Each bar will be returned to its own container after measurement has been taken.
9. Calculate the difference between the relative zero reading of the bar and the reading at each period to the nearest 0.001% of the effective gage length and record the reading as the expansion of the bar for that period.

EXPERIMENTAL PROGRAM

The experimental program comprised of two distinct phases: (A) NJDOT class A mixtures; (B) optimized mixtures. Both phases included development of four mixtures by using various recycled materials. In addition to the mixtures containing recycled materials, a control mix containing ordinary constituents (cement: sand: gravel: water) was prepared for comparison. Mix designs were developed by using NJDOT specifications. The experimental program in both phases included the following mixtures:

1. Normal Concrete (NC) Test
2. Cementitious concrete or concrete containing blast furnace slag and other cementitious materials (CC).
3. Concrete containing crushed glass (CGC)
4. Concrete containing street sweepings (SSC)
5. Concrete containing recycled concrete aggregate (RCA)

The above-mentioned materials were selected by the Recycled Materials Task Groups due to obvious environmental advantages associated with the use of recycled materials in concrete. For instance, glass is not biodegradable and its use in concrete will have a great consequence in freeing up the needed landfill space. Street sweepings may provide a viable alternative to fine aggregates in concrete. Studies pertaining to the use of street sweepings in concrete are scarce. It is believed that they can contain contaminants (petroleum based), and that may have deleterious effects on concrete mixes. The present determined some of the unknowns associated with that mix. In addition, incorporation of selected materials in concrete may also provide additional benefits in terms of improvements to concrete durability, strength, and aesthetics of construction.

PHASE A – NJDOT CLASS-A MIXTURES

Two versions of class-A concrete were used with the recycled materials. The first mixture pertained to a standard class-A mix, and the second one included cementitious components (GGBFS, and SF). The general class-A mix specifications per cubic yard of concrete are given in table 1. A total of seven different mix types, including the control mix were considered for preparation of cylindrical and beam specimens. At least two batches were prepared per mix type. Mix categories are defined in table 2, and tables 3 through 10 detail the finalized mix proportions and actual weights of the constituents per mix type. It was not possible to produce workable batches of concrete with street sweepings, even by doubling the water-to-cement ratio. However, tables 6 and 7 are given here and left out empty to indicate that many trials were made with street sweepings both with class A as well as the cementitious mix types.

Table I Mix Proportions for typical NJDOT class A concrete

Class A concrete (1 Cu.Yd.)	Lbs.	Oz. cwt
Coarse Aggregate	1640	
Fine Aggregate	1350	
Water	263	
Cement	611	
Water Reducer (Sika Plastiment)		24
Air Entraining Admixture (Sika AER)		4.5

Table 2 Mix Type Designations and Descriptions.

Mix Type Number	Mix Type Description
1	NJDOT Class A (Control Mix Type)
2	Class-A with Recycled Glass
3	Cementitious Mix with Glass
4	Class A with Street Sweepings
5	Cementitious Mix with Street Sweepings
6	Class A with Recycled Concrete
7	Cementitious Mix with Recycled Concrete

Table 3 Typical laboratory batch proportions for type 1 mix.

Class A concrete	Lbs.	Oz.
Coarse Aggregate	69	
Fine Aggregate	57	
Water	11	
Cement	26	
Water Reducer (Sika Plastiment)		1
Air Entraining Admixture (Sika AER)		0.2

Table 4 Typical laboratory batch proportions for type 2 mix.

Class A with Recycled Glass	Lbs.	Oz.
Coarse Aggregate	34.92	
Fine Aggregate	49.66	
20% Glass Replacement	8.73	
Water	7.99	
Cement	18.5	
Water Reducer (Sika Plastiment)		0.8
Air Entraining Admixture (Sika AER)		0.14

Table 5 Typical laboratory batch proportions for type 3 mix.

Cementitious Mix with Recycled Glass	Lbs.	Oz.
Coarse Aggregate	34.92	
Fine Aggregate	49.66	
20% Glass Replacement	8.73	
Water	7.99	
Cement	10.97	
Silica Fume	1.83	
GBFS	5.49	
Water Reducer (Sika Plastiment)		0.73
Air Entraining Admixture (Sika AER)		0.14

Table 6 Typical laboratory batch proportions for type 4 mix.

Class A with Street Sweepings	**Lbs.**	**Oz.**
Coarse Aggregate		
Street Sweepings	Many Trials with various proportions and the mix did not work	
Fine Aggregate		
Water		
Cement		
Water Reducer (Sika Plastiment)		
Air Entraining Admixture (Sika AER)		

Table 7 Typical laboratory batch proportions for type 5 mix.

Cementitious Mix with Street Sweepings	**Lbs.**	**Oz.**
Coarse Aggregate		
Street Sweepings	Many Trials with various proportions and the mix did not work	
Fine Aggregate		
Water		
Cement		
Water Reducer (Sika Plastiment)		
Air Entraining Admixture (Sika AER)		

Table 8 Typical laboratory batch proportions for type 6 mix.

Class A Mix with Recycled Concrete	**Lbs.**	**Oz.**
Coarse Aggregate	35	
Recycled Concrete	35	
Fine Aggregate	57	
Water	11	
Cement	26	
Water Reducer (Sika Plastiment)		1.0
Air Entraining Admixture (Sika AER)		0.2

Table 9 Typical laboratory batch proportions for type 7 mix.

Class A Mix with Recycled Concrete	Lbs.	Oz.
Coarse Aggregate	35	
Recycled Concrete	35	
Fine Aggregate	57	
Water	11	
Cement	15.5	
Silica Fume	2.6	
GBFS	7.7	
Water Reducer (Sika Plastiment)		1.0
Air Entraining Admixture (Sika AER)		0.2

Phase-A Experimental Results

The experimental results are presented here and they correspond to the 28-day compressive strength and the durability characteristics in terms of Alkali silica Reactivity (ASR) and Chloride permeability of the concrete samples. Compressive strength data presented here correspond to average of two tests, and as per ASTM standard, the three tests were performed in case of more than 10% discrepancy in the strength data. Table 10 lists the 28-day compressive strength data for all the mix types. ASR tests pertained to the specifications set by ASTM C1260. Expansion of the mortar bars for all mix types in 3, 7 and 14 days as per the specification of ASTM C1260 was monitored and measured. ASR test results in terms of mortar bar expansions are given in table 11.

Permeability tests were conducted in accordance with ASTM C1202, " Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration". As discussed earlier, the basic method of permeability test is by means of measuring the electrical conductance of concrete to evaluate resistance of concrete to chloride ion penetration. Permeability test results in Coulombs are given in table 12.

Discussion of Phase-A Results and Recommendations

In general, the performance of the Class-A concrete made with recycled materials was not acceptable. The compressive strength requirements were within the minimum range of specifications. Yet, most of the samples failed the durability tests. Apart from the cementitious mix types (mix types 3 and 7) which indicated very low permeability, the class A mix types' permeability results indicated moderate ion penetration based on the charge passed through the samples. Alkali-Silica reactivity observed in class A concrete samples containing recycled materials. ASR test results were indicative of excessive expansions except for the cementitious mixtures (Mix types 3 and 7). As per specifications, C1260 or T214, expansion of shrinkage bars equal to or greater than 0.02% in 14-days indicate potentially deleterious expansion. Accordingly, table 11 indicates ASR activity in all the class A mix types. At this point, results from this study indicates that the recycled materials are not suited for use with class-A concrete unless the mixture is optimized with cementitious materials and other additives to remedy the durability problems.

Table 10 Compressive strength data.

Concrete Mix Type No.	28-day Compressive Strength (psi)	Average (psi)
1 (Control mix)	4759 4349 4182	4265 (Avg.of 2)
2	4790 5050	4920
3	5892 5728	5810
4	-	
5	-	
6	5068 4141 4495	4318 (Avg. of 2)
7	4979 4800 5317	4889 (Avg. of 2)

Table 11 ASR test results in terms of mortar bar expansions.

Mix Type No.	Percent Expansion (%)		
	3-day	7-day	14-day
1	0.0098	0.0098	0.033
2	0.0185	0.031	0.150
3	0.0075	0.0075	0.010
6	0.0095	0.042	0.053
7	0.0015	0.003	0.018

Table 12 Chloride Ion Permeability test results in terms of Charge Passed.

Mix Type No.	6-hr. Coulombs (AVG. of 2 tests)
1	2278 (2000-4000 Moderate)
2	2826 (2000-4000 Moderate)
3	214 (100-1000 Very Low)
6	2449 (2000-4000 Moderate)
7	188 (100-1000 Very Low)

PHASE B – OPTIMIZED MIXTURES

Experimental results presented in Phase-A of the project indicated that introduction of recycled materials in class-A concrete without any modifications to the mix will result in unacceptable concrete. This fact was known in advance, and in fact Phase-B of the project was performed prior to Phase-A. Reports 1 through 4 submitted to NJDOT details all the mixtures and test results. The primary objective of the work performed during Phase-B of the project was to develop an optimized mix design for use with the recycled materials. The optimized mix designs, as indicated in the prior reports showed superior performance for all the materials tested (Crushed Glass, Street Sweepings, and Recycled Concrete). However, Phase-A results indicated that street sweepings are of variable quality, depending on the origin and source. While Phase-B experiments produced successful results with street sweepings, it was not possible to even develop any mixtures with these materials during Phase-A of the project. Results form both phases indicated that Recycled Crushed Glass (CGC) and Recycled Concrete (RC) show potential with cementitious mixtures. Phase-B part of the study was performed to establish optimum mixtures to enhance durability and strength characteristics of concrete made with these recycled materials. Selected results from Phase-B pertaining to CGC and RC concrete will be reiterated here for completeness. As discussed earlier, this study does not recommend the use of street sweepings in concrete due to high variability in the material.

Crushed Glass Concrete

The crushed glass concrete (CGC) mix was developed and compared with a control base mix consisted of normal concrete. The crushed glass concrete mix contained crushed glass with ordinary concrete constituents in addition to cementitious materials such as blast furnace slag (BFS), and silica fume (SF) and chemical admixtures such as lithium hydroxide. The cementitious concrete mixes developed at stage 2 of the research, refer to establishment of a number of trial mixtures for describing the optimum proportion of Blast Furnace Slag (BFS). The optimum proportion of cementitious materials adopted for this stage of the project was 40%, where 30% BFS and 10% SF. Four different mixes containing 5, 10, 15 and 100 percent crushed glass (mass ratio) were used as a replacement of the normal coarse aggregate. Compressive and flexural strengths were determined through repeated tests.

The crushed glass concrete mix was proportioned in a way to minimize the expansion due to Alkali Silica Reactivity (ASR). In general, the average compressive strength of crushed glass concrete containing 5% CG was higher than the 10, 15 and 100 percent CG concrete. The average compressive strength of moist cured crushed glass concrete mixtures ranged from 5431 psi for 5% CG to 3661 psi for 100% CG at 28 days. Based on the findings of this phase of the study, the crushed glass concrete developed here had shown no expansion due to ASR. It was evident that cementitious materials, which had been used in the CGC mixtures, had enhance the properties of CGC in terms of mechanical strength and durability, especially in terms of alkali silica reactivity. Also, the permeability of CGC was satisfactory. On the other hand, the compressive strength of hardened CGC had proportionally decreased with the increase of curing age. This suggests that long-term properties of CGC may not be as promising as the short-term results suggest. Therefore, CGC shall not be used in structural and load bearing applications.

Optimized mix proportions for CGC is detailed in Table 13. As shown, the optimized mixture contains a relatively large amount of cementitious materials as well as Lithium. Incorporation of Blast Furnace Slag served a dual purpose as a recycled material as well as a durability performance enhancer. Lithium was purposely added to suppress Alkali-Silica-Reactivity. The mechanical characteristics are shown in table 14. Tables 15, and 16 pertain to chloride permeability and ASR test results. As shown chloride permeability has been totally suppressed, although the potential for ASR still exists. In Figs. 1 through 4 compressive strengths of various CGC mixtures (5% through 100%) have been compared in terms of curing age. Fig. 5 corresponds to comparison of the 28-day compressive strength for all the mixtures. As indicated earlier, the loss of compressive strength with age is a problem with CGC material.

Talbe 13 Mix Proportions for Crushed Glass Aggregate Concrete

CG Proportions	5% (lb/yd^3)	10% (lb/yd^3)	15% (lb/yd^3)	100% (lb/yd^3)
Crushed Glass	88	176	264	1763
Water	354	354	354	354
Cement	432	432	432	432
BF Slag	186	186	186	186
Silica Fume	46	46	46	46
Coarse Aggregate	1675	1587	1499	0
Fine Aggregate	1275	1275	1275	1275
Lithium	2.6	2.6	2.6	2.6

Table14 CGC Compressive and Flexural (Modulus of Rupture) Strength Test Results.

CG Proportion	Curing Days	Cylinders No.	Compressive Strength (psi)	Beams No.	Modulus of Rupture (psi)
5%	14	1	4616		
	28	2	5684	1	521
		3	4878	2	748
		4	5731	3	/
		average (28days)	**5431**	average	**635**
	56	5	5338		
10%	14	1	5412		
	28	2	5453	1	678
		3	5412	2	713
		4	5253	3	653
		average (28days)	**5373**	average	**681**
	56	5	4408		
15%	14	1	3979		
		2	4935	1	601
	28	3	5116	2	670
		4	4580	3	740
		average (28days)	**4877**	average	**670**
	56	5	4309		
100%	14	1	3183		
	28	2	3820	1	538
		3	3342	2	565
		4	3820	3	604
		average (28days)	**3661**	average	**569**
	56	5	3127		

Table 15 Permeability Test Results for CGC

Material	Proportion (%)	Curing Days	Coulombs	Chloride Permeability
CGC	30	58	288	very low
	40	56	237	very low
	50	51	576	very low
	100	49	409	very low

Table 16 ASR test results for CGC concrete.

Concrete	Bar No.	Bar L_0 (in)	0 day (%)	1st (%)	4th (%)	7th (%)	11th (%)	14th (%)	21st (%)	28th (%)
Crushed Glass	1	10.253	0.047	0.021	0.02	0.048	0.039	0.044	0.057	0.091
	2	10.274	0.059	0.01	0.034	0.082	0.093	0.095	0.115	0.133
	3	10.244	0.097	0.011	0.016	0.057	0.045	0.027	0.055	0.09
	4	10.260	0.115	0.01	0.012	0.024	0.027	0.026	0.052	0.097
	average			**0.013**	**0.021**	**0.053**	**0.051**	**0.048**	**0.070**	**0.103**

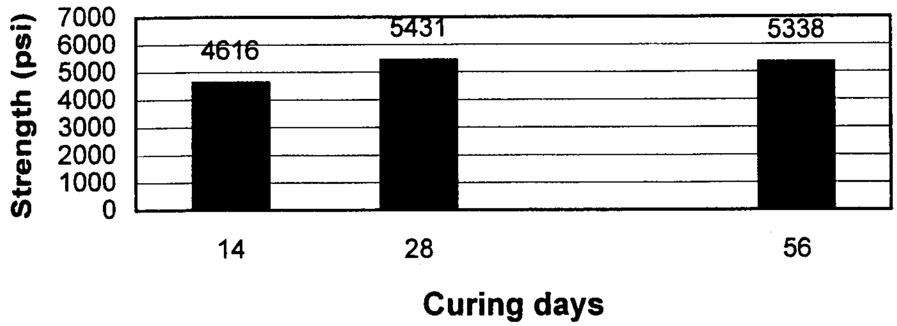

Figure 1. Change in compressive strength as a function of age for 5% CGC.

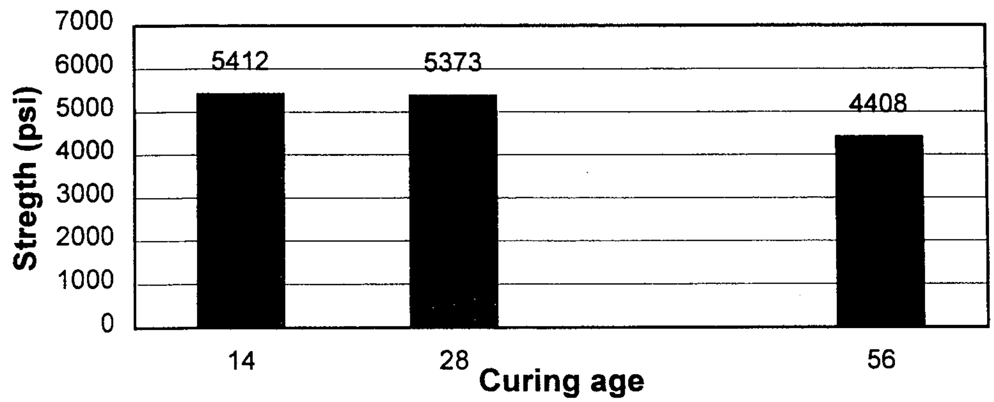

Figure 2. Change in compressive strength as a function of age for 10% CGC.

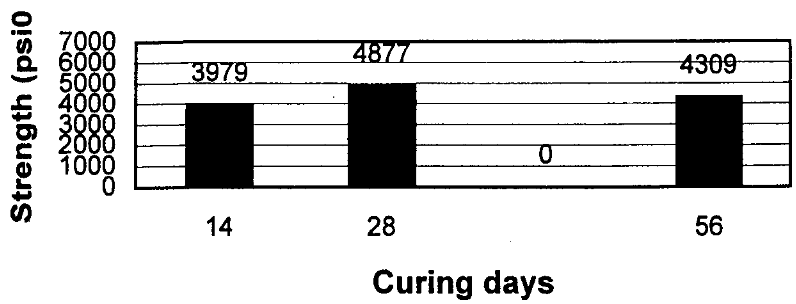

Figure 3. Change in compressive strength as a function of age for 15% CGC.

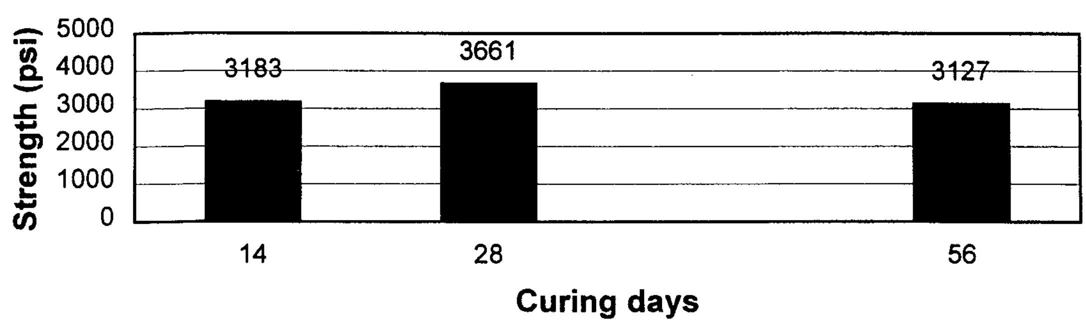

Figure 4. Change in compressive strength as a function of age for 100 % CGC.

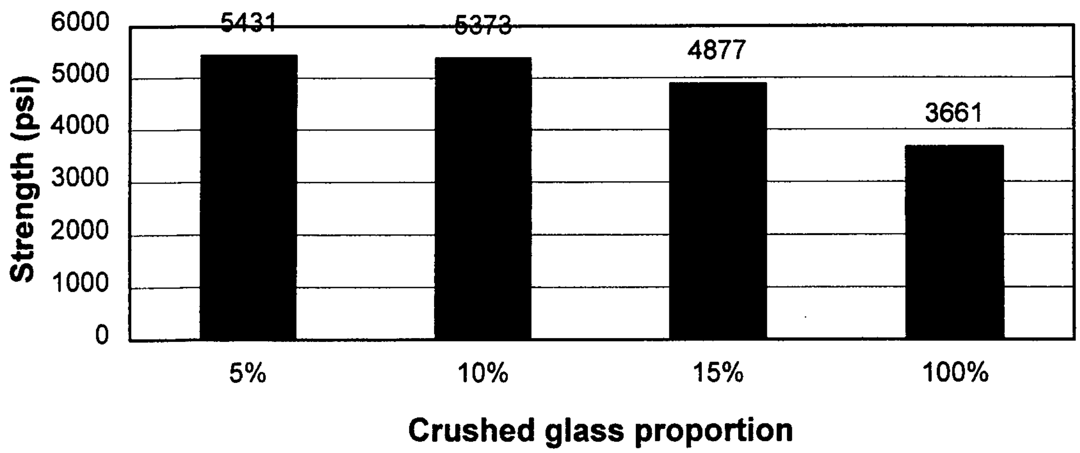

Figure 5. Comparison of 28-day strengths for all the CGC concretes.

Recycled Aggregate Concrete

The recycled aggregate concrete mix (RCA) involved involved constituents found in normal concrete mixtures and other materials including blast furnace slag, silica fumeand lithium hydroxide. Two different mixes containing 50% and 100% of recycled concrete as coarse aggregate (mass ratio) was employed. Mix design for the two RCA mixtures are outlined in Table 17. Permeability test results for RCA concrete are given in Table 18. as shown, the optimized mix produced a very dense product and resistance against chloride ion ingress. Table 19 pertains to the mechanical properties in terms of compressive strength and modulus of rupture for RCA concrete. As shown in Fig.6, increase in the proportion of RCA reduces the 28-day strength of concrete.

Table 17 RCA mix design.

RCA Proportions	50% (lb/yd^3)	100% (lb/yd^3)
RC Aggregate	896	1793
Water	330	305
Cement	432	432
Blast Furnace Slag	186	186
Silica Fume	46	46
Coarse Aggregate	882	0
Fine Aggregate	1275	1275
Lithium	2.6	2.6

Table 18. PERMEABILITY TEST RESULT

Material	Proportion (%)	Curing days	Coulombs	Chloride permeability
RCA	50	36	561	very low
	100	36	569	very low

Table 19. Compressive Strength and Modulus of Rupture for RCA concrete.

RCA proportion	Curing days	Compressive Strength (psi)	Modulus of Rupture (psi)
0%	14	4935	
	28	5465	682
	56	5731	
50%	14	4326	
	28	4824	504
	56	4830	
100%	14	3786	
	28	3769	525
	56	3933	

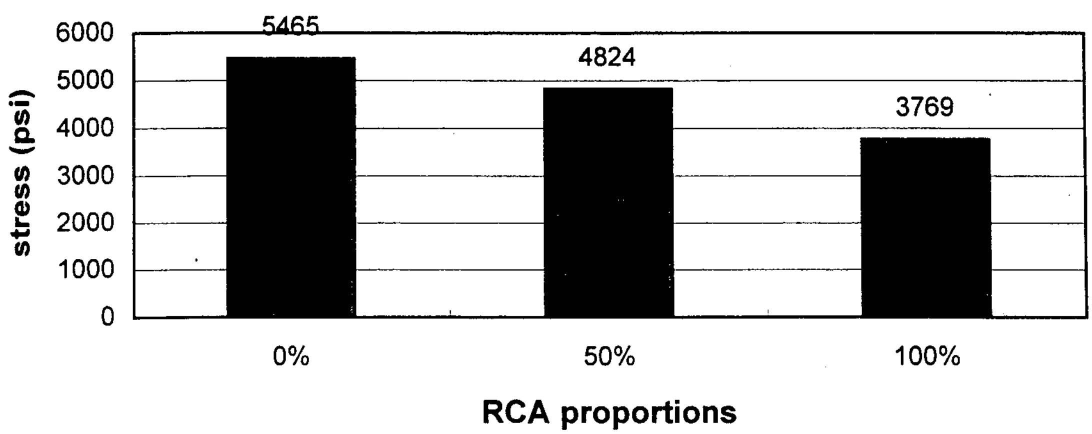

Figure 6. Comparison of the 28-day strength for concretes with various percentages of RCA as coarse aggregate.

CONCLUSIONS

This study is part of a comprehensive research investigating the mechanical and durability attributes of concrete made with recycled materials. The recycled materials studied were crushed glass, street sweepings, recycled concrete, and blast furnace slag was used to enhance properties. This report details the investigations in Phase A of the project corresponding to class A concrete. Previous reports (reports 1 through 4) provides details for Phase B of the project.

Based on the results of this study, it is recommended that street sweepings shall not be used with any type of concrete mixture due to its variability. Crushed glass and recycled aggregate concrete shall be used with optimized cementitious mixtures and not standard class A concrete. These recommendations are mainly based on the decreased durability attributes of such materials. Even with the optimized cementitious mixtures, the reduction in compressive strength as a function of curing age for crushed glass concrete points at uncertainty regarding the long term load bearing characteristics of such material. It is recommended that the crushed glass concrete not to be used in structural and load bearing applications. Recycled concrete can be used for secondary applications and it possesses enhanced durability attributes in optimized, cementitious mixtures.

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