Coventry University and
The University of Wisconsin Milwaukee Centre for By-products Utilization
Second International Conference on Sustainable Construction Materials and Technologies
June 28 - June 30, 2010, Università Politecnica delle Marche, Ancona, Italy.
Proceedings of Honouree sessions ed. T Naik, F Canpolat, P Claisse, E Ganjian,
ISBN 978-1-4507-1487-7 http://www.claisse.info/Proceedings.htm

How Can Aggregates be Used to Enhance Sustainable Concrete?

David W. Fowler

The University of Texas at Austin, 1 University Station, Austin, Texas 78712, USA. E-mail: <*dwf@mail.utexas.edu*>

ABSTRACT

Since aggregates are the most widely used construction material, it is essential that they be at the forefront of sustainable construction. Sustainability can be achieved in several ways: (1) Making use of all the aggregate micro fines that are produced that are often considered waste materials. Research has shown that in most cases all the micro fines produced during crushing, up to 20% of the total fine aggregates, can be used by proper mixture proportioning. (2) Using all aggregates produced by proper engineering. Many aggregate sources are susceptible to alkali-silica reaction, but by proper mitigation methods they can safely and effectively be used. In many cases ASR can be mitigated by using supplementary cementing materials, in which sustainable materials are used to increase the use of another sustainable material. (3) Using recycled concrete as aggregate in producing concrete mixtures. Recycled concrete can be used for many applications, particularly as coarse aggregate for producing quality concrete.

INTRODUCTION

Aggregates are the most widely used construction materials in the world. Concrete pavements, bridges, foundations, dams, utilities, buildings and other structures would not be possible without aggregates, particularly when used to produce concrete. Aggregates are produced in essentially every nation and every region within nations. They are among the least expensive building material, and even when used in concrete as 75 or 80% of the total mixture, aggregates are still less expensive than cement. In some areas, transportation costs exceed the on-site cost of aggregates.

Aggregates come from many mineralogies. Some are “natural”, used as they are found in nature (usually after washing) and some are “manufactured,” crushed from stones that are quarried. With the concerns about the environment, it is becoming more difficult to obtain approval to mine natural aggregates near rivers and waterways where they are normally found. Manufactured aggregates will likely be used more and more. Figure 1 shows the production of natural and manufactured aggregates in the U.S. projected through 2020.

It is clear that manufactured aggregates will increase in relation to natural aggregates in the future in the U.S., and this trend is likely in many other parts of the world. The use of manufactured aggregates poses some challenges. Due to their angular shapes they produce concrete that is not as workable. The increased amount of dust of fracture or micro fines (material that passes the 75 µm sieve) often increases water demand and may require use of admixtures to yield concrete with the desired workability.

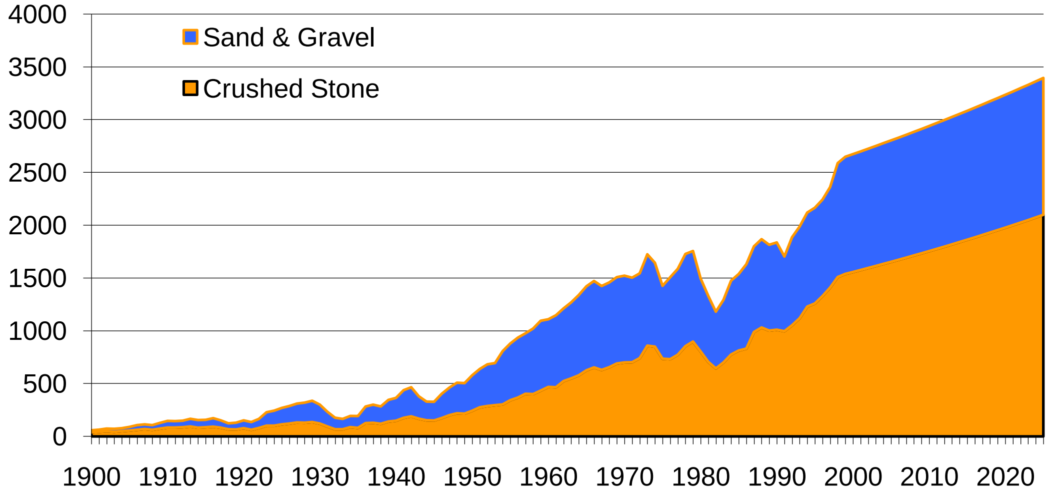


Fig. 1. Production of Aggregates in the U.S.

The use of some aggregates, particularly silica aggregates, can result in alkali-silica reaction (ASR) that is very destructive. The challenge is to produce concrete that minimizes the effect of ASR

Large volumes of recycled concrete are available for use as aggregates. The challenges related to their use for use in concrete relate to their variability that affects absorption, durability and workability. Fine aggregates produced in crushing concrete have created special challenges for use in concrete.

All of our aggregates must be used effectively. Transporting “high quality”aggregates long distances uses additional energy and produces more CO^2. By proper engineering local aggregates can be used to produce quality concrete or in other applications such as roadway bases or embankments.

This paper will address three areas of aggregates for concrete related to sustainability:

- Incorporating micro fines to produce quality concrete;
- Using aggregates subject to ASR by using proper mitigation; and
- Using recycled concrete as aggregate.

USE OF MICRO FINES TO MAKE QUALITY CONCRETE

Background. Crushing stone to make aggregates produces large amounts of very fine particles, often referred to as crusher fines, dust of fracture, or micro fines. These are particles that pass the 75µm sieve and are often considered to be waste materials that require washing or other forms of removal prior to use in concrete. The major challenge in the U.S. is the current grading standard for fine aggregate which is based on ASTM C 33 Concrete Aggregates. This specification has been the standard for many years and was originally developed for natural sand. Manufactured fine aggregate (MFA) is much more variable in size, and generally contains much larger percentages of micro fines than permitted. (C 33 permits a maximum of 7% except when used in abrasive environments the limit is 5%). In the past the micro fines have had to be removed and generally are considered to be waste materials. Sustainability requires that these materials be used, and research has shown that micro fines can produce quality concrete.

Research. In one of the first large scale research programs at the International Center for Aggregates Research (ICAR) at The University of Texas at Austin, a large number of aggregate sources representing all the major mineralogies from around the U.S were crushed in the same crusher (Ahn, 2001), and ten manufactured fine aggregates and one good quality natural sand were used to make concrete. The MFAs as produced failed to meet the ASTM C 33 grading specifications in three to five size fractions (Table 1). The amount of micro fines ranged from 4.5 to 16.7% by weight of the MFA. Concrete was made with 19-mm limestone coarse aggregate, ASTM Type 1 cement, 42% sand based on total aggregate volume and no admixtures. The two control variables were (1) fixed water-to cement ratio (w/c) of 0.53 and (2) fixed slump of 50 to 100 mm. The aggregates are designated as follows: limestone, LS; granite, GT; quartzite, QZ; diabase, DI; dolomite, DO; basalt, BA; and sandstone, SS.

Table 1. Grading of Aggregates Used in Study

	Cumulative percent passing of sample							passing
Type	**9.5mm**	**4.75mm**	**2.36mm**	**1.18mm**	**600µm**	**300µm**	**150µm**	**75µm**
LS-1	100.0%	100.0%	82.5%	56.5%	36.6%	24.6%	17.6%	14.3%
GT	100.0%	100.0%	86.0%	65.5%	47.9%	34.3%	22.1%	13.3%
QZ	100.0%	100.0%	78.0%	62.2%	50.6%	37.3%	22.7%	13.5%
DI	100.0%	100.0%	77.7%	57.6%	42.4%	31.6%	22.6%	15.8%
DO	100.0%	100.0%	78.0%	55.1%	38.8%	29.0%	21.8%	16.7%
LS-2	99.9%	96.4%	66.4%	38.0%	22.2%	13.5%	8.0%	4.5%
LS-3	100.0%	97.3%	76.0%	49.5%	33.2%	24.0%	18.0%	13.3%
LS-4	100.0%	97.0%	69.1%	39.2%	23.9%	15.9%	11.0%	7.4%
BA	100.0%	100.0%	68.1%	48.0%	35.8%	27.2%	20.0%	14.3%
SS	100.0%	100.0%	72.9%	55.8%	44.9%	31.6%	17.0%	10.3%
ASTM C33	100.0%	95-100%	85-100%	50-85%	25-60%	10-30%	2-10%	< 7%

The concretes, produced without mineral or chemical admixtures, generally had good workability. The compressive strengths for the fixed w/c are shown in Fig. 1. All but one of the MFAs produced higher compressive strength than for the natural sand control. The flexural strengths (Fig. 2) for fixed w/c were higher for all MFA concretes, some significant amounts. Abrasion loss using ASTM was less than the control for all MFA concretes tested (Fig. 3). This is significant since ASTM C 33 limits the amount of micro fines to 5% in applications involving abrasion but permits up to 7% in other applications. There appears to be no reason for this lower limit based on many concretes tested. Drying shrinkage using ASTM C 157 varied considerably with about half the MFA concretes having more shrinkage than the control, although the values are not excessive (Fig. 4).

For tests involving fixed slump, the average w/c was 0.56, with one material requiring 0.59. Four materials achieved the desired slump at the w/c = 0.53.

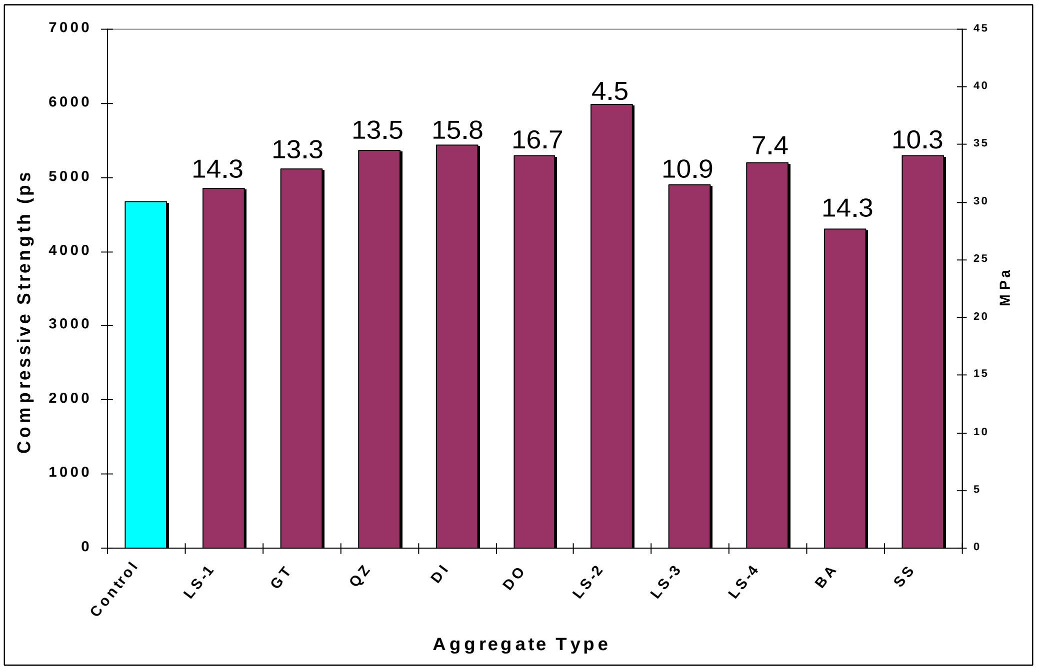


Fig. 2. Compressive Strength by Type and Microfine Percentage

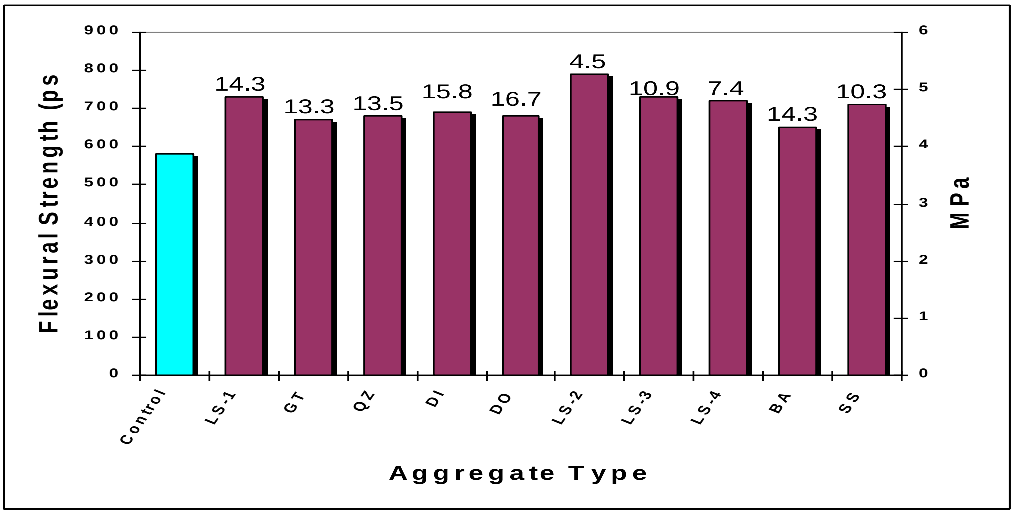


Fig. 3. Flexural Strength by Aggregate Type and Microfine Percentage

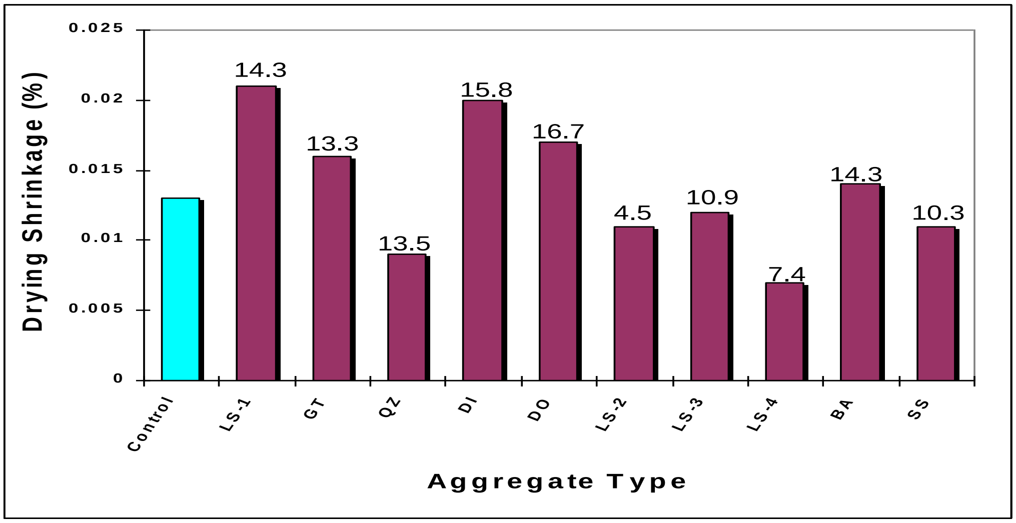
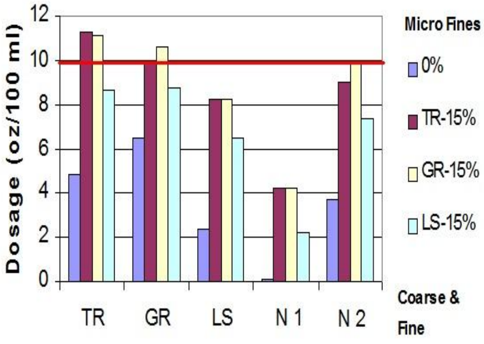


Fig. 4. Drying Shrinkage by Aggregate Type and Microfine Percentage

In a follow up research program, both chemical and mineral admixtures were used to improve workability (Quiroga, 2004; Quiroga, 2005). In this research, trap rock (TR), granite (GR), limestone (LS) and two natural aggregates (N1 and N2) were used to produce the concrete. The fine aggregates were sieved and regraded to yield the same gradations that met C 33. For each of the five mineralogies, concrete was made using the coarse and fine aggregates. In addition, concrete was made with aggregates of each mineralogy separately using 15% (by weight of the fine aggregate) of each type of micro fines, e.g. for trap rock coarse and fine aggregate, concretes were made using each of the three types of micro fines. Figure 5 shows the amount of high range water reducer (HRWR) to yield a 125-mm slump. The horizontal line represents the manufacturer's recommended maximum dosage. The required dosages ranged from none for the natural N1 coarse and fine with no micro fines to over 11oz/100 ml when trap rock coarse and fine with trap rock micro fines. The limestone micro fines required the least amount of water reducer, reflecting the improved shape of the material. Figure 6 shows that the 28-day flexural strengths are generally improved by adding micro fines with the trap rock micro fines generally producing the highest strengths. The 28-day drying shrinkage values are shown in Fig. 7 for concrete with w/c = 0.41, with the same coarse and fine aggregate and different types and percentages of micro fines. Mixtures with and without high range water reducer were used. The concretes with micro fines yielded slightly higher shrinkages than the control, and the use of HRWR gave slightly lower values compared to concretes without water reducer.

In summary, extensive research has shown that nearly all micro fines up to 15 or 20% by weight of the fine aggregate can be used to make good quality concrete with good workability that often is superior to concrete without micro fines. It is important to test for clays, e.g. the methylene blue test, since clay can result in reduced performance concrete.



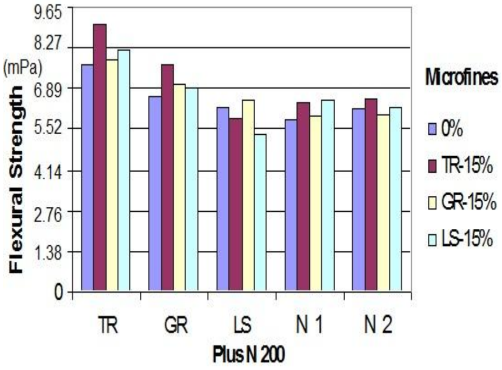


Fig. 5. HRWR Required to Yield 125-mm Slump

Fig. 6. Flexural Strength

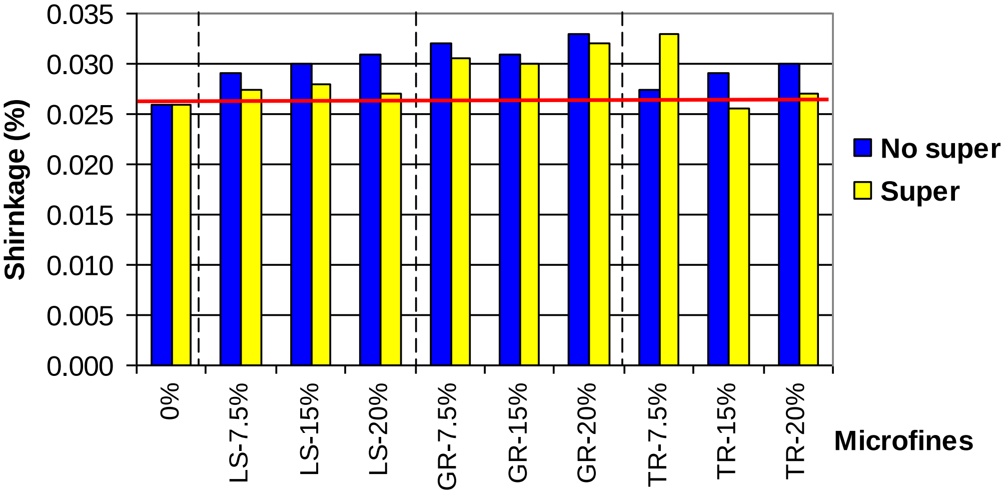


Fig. 7. 28-day Drying Strength by Microfine Type and Percentage

Use of Mitigation for Aggregates Subject to ASR

Nearly every state in the U.S. (and most countries around the world) has aggregates that exhibit alkali-silica reaction (ASR) for some applications. For many years, specifications were written to exclude the use of these aggregates when the environment was conducive to promoting ASR. However, sustainability requires that all aggregates be used if at all possible by using appropriate mitigation methods.

ASR occurs when reactive silica in certain aggregates is exposed to sufficient alkali (primarily from portland cement but also from other cementing materials, some chemical admixtures, some aggregates and external sources of seawater and deicing chemicals), and sufficient moisture. Alkali-silica gel forms around the aggregate and, when exposed to additional moisture, expands resulting in internal stresses and eventually cracking. Water can then penetrate the cracks and the distress continues. (If the relative humidity is maintained at levels below 80%, there is little likelihood of significant expansion occurring.) Pavements, sidewalks, walls, hydraulic structures and other structures containing reactive silica aggregates and exposed to moister are particularly prone to ASR distress.

Two tests are most commonly used to test for the potential for aggregates to exhibit ASR. The mortar bar test (ASTM C 1260) requires a test period of 14 days but often excludes aggregates that are known to perform well in the field. The more realistic test, that uses a concrete prism (ASTM C 1293), requires a minimum of one year and even longer when supplementary cementing materials (SCMs) are used in the mixture. Some specifications permit the use of the mortar bar, but if the expansion exceeds the specified limits, the concrete prism is then used. But the question is: if it fails the prism test, can the aggregate be used? This is where mitigation comes in. By properly engineering the mixtures most reactive aggregates can be used (Folliard, 2006).

It was initially thought that if cements with low alkali contents, e.g. less than 0.6% were used, that ASR would not occur. It is now understood that it is the total alkalis in the concrete that is the important variable rather than the alkali content of the cement only. So mitigation must include more than limiting the alkali content of the cement.

One of the most effective mitigation methods is the use of SCMs such as fly ash, silica fume, slag and ternary blends, which in turn promotes sustainability leading to a win-win situation. When added to the concrete mixture, SCMs reduce or eliminate ASR by:

- Reducing concrete permeability
- Reducing ionic mobility
- Reducing pore solution alkalinity (depending on the type and amount of SCM) due to pozzolanic reaction and alkali binding.

Fly ash is an effective SCM or mitigating ASR. Figure 8 shows results of the ASTM C 1293 prism test on a control mixture with no fly ash and four mixtures containing 25% fly ash each with a different calcium oxide (CaO) content (Shehata, 2000). The concrete contained a siliceous limestone. It is clear that the expansion was significantly reduced as the CaO content was reduced. The reasons for the increased effectiveness of low CaO ashes is that they reduce pore solution pH more effectively and produce C-S-H that binds significant amounts of alkalies, further reducing pore solution pH.

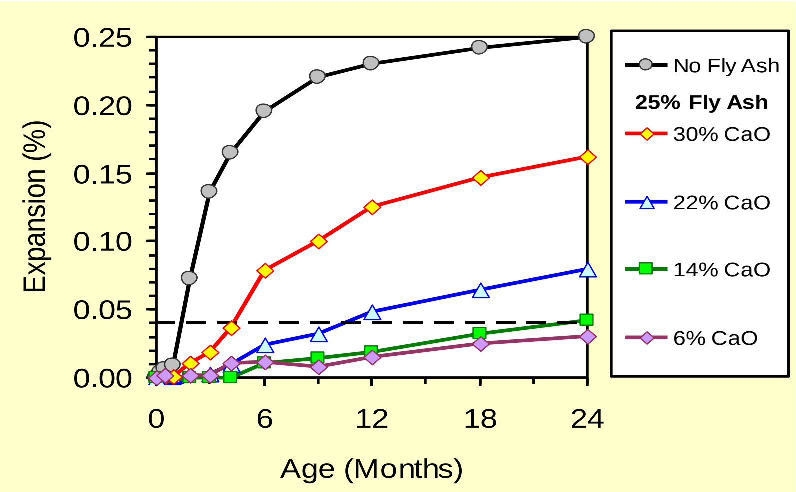


Fig. 8. C 1293 Expansion for Fly Ash with Different Levels of CaO (Shehata, 2000)

Ground granulated blast furnace slag (GGBFS), a by-product of the iron-making industry has also been shown to be an effective material for mitigation of ASR. Figure 9 shows the effect of various cement replacement levels of slag on the expansion of a concrete containing a siliceous limestone (Thomas, 1998). For expansions measured over two years, 50% slag was found to limit the expansion to acceptable levels.

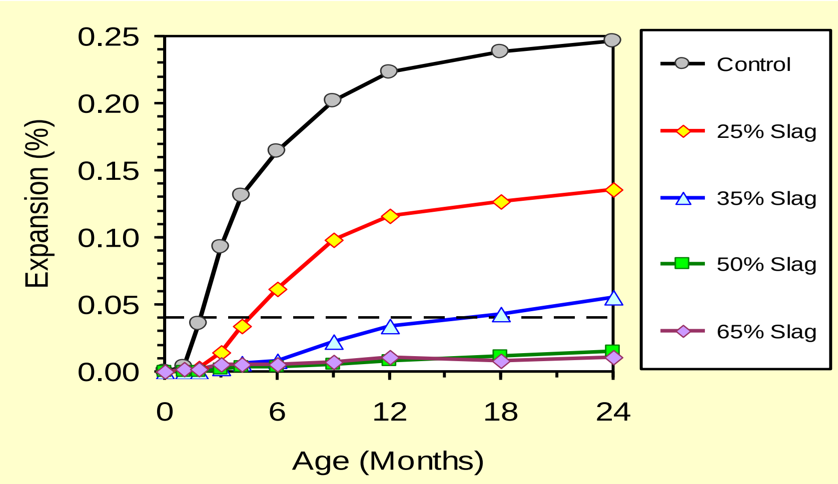


Fig. 9. C 1293 Expansion for Various Levels of Slag (Thomas, 1998)

Silica fume, a by-product of the silicon metal and silicon-iron making industry, is an extremely fine and reactive pozzolan. It has been widely used in high strength and high performance concrete. It is effective in mitigating ASR although its use is not as well established as fly ash and slag. Figure 10 shows the expansion for different levels of silica fume addition as a replacement of cement (Fournier, 2004). For this application it would require a replacement of about 10%.

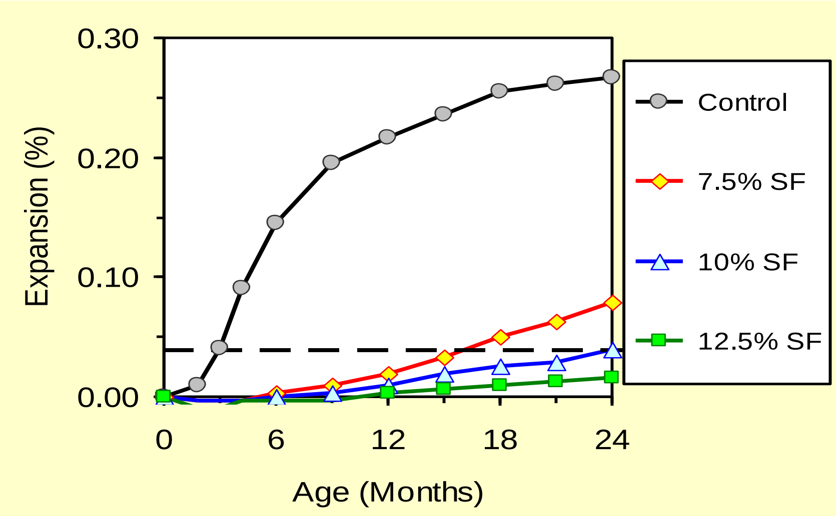
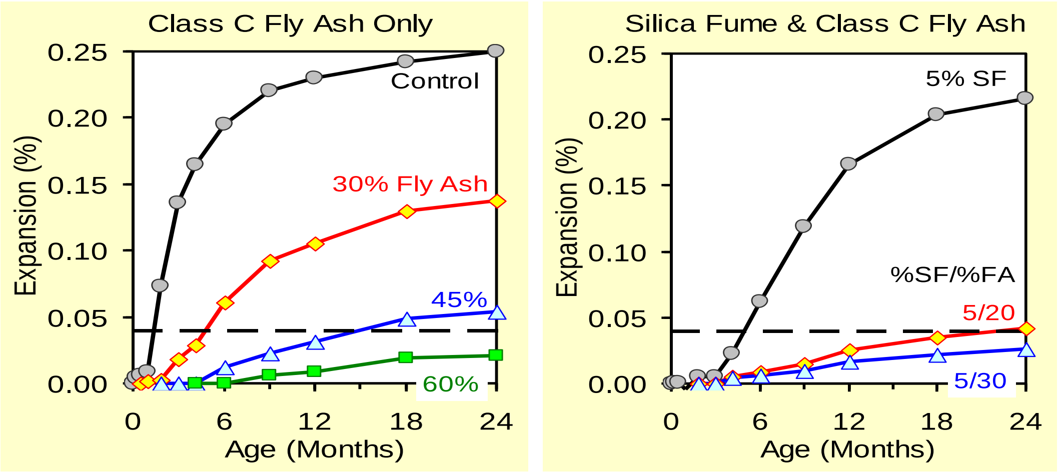


Fig. 10. C 1293 Expansion for Various Levels of Silica Fume (Fournier, 2004)

Ternary blends, containing portland cement and two SCMs, have proven to be very effective in mitigating ASR. Figure 11 illustrates the synergistic effect of using fly ash and silica fume (Shehata, 2002). The use of 5% silica fume is seen to reduce the expansion only slightly in a mixture containing a highly reactive aggregate compared to the control mixture, but when 30% Class C fly ash was added the combined effect was much greater than for either SCM alone.



(a) (b)

Fig. 11. C 1293 Expansion of Class C Fly Ash (a) and Fly Ash Combined with Silica Fume (b) (Shehata, 2002)

An example of a prescriptive specification for instances when reactive aggregates are to be used could be:

- Limit the alkali content in concrete to 3 kg/m^3
- Use a minimum of 50% slag
- Use a minimum of 50% slag
- Use a minimum of 20% Class F (low CaO) fly ash
- Use a minimum of 10% silica fume
- Use a minimum of 5% silica fume and 30% Class C (high CaO) fly ash.

Use of Recycled Concrete as Aggregate

Use of recycled concrete as aggregate for producing concrete is an important development in promoting sustainability. Rather than relegating crushed concrete to landfills or low tech uses such as embankments, why not reuse it to make quality concrete? The highway industry has been proactive in using recycled concrete for pavement subbase layers or for new concrete paving. In the U.S., the Federal Highway Administration reported that 38 states now use recycled concrete for aggregate base and 11 use it in new portland cement concrete.

The American Concrete Institute has issued a report (ACI, 2001) on “Removal and Reuse of Hardened Concrete” that provides guidelines for production of concrete from recycled concrete. It addresses:

- Aggregate production process
- Aggregate quality
- Effects of recycled aggregates on concrete properties
- Mixture proportions
- Concrete production

One of the concerns with recycled concrete is contamination. Steel reinforcing is often present and can be removed, but of more concern are contaminants including wood, paper, plaster, plastic, oil, and salt. The recycled concrete must be properly sorted and cleaned to make quality concrete. ACI recommends that both fine and coarse recycled aggregates have 10 kg/m^3 or less plaster and clay lumps and 2 kg/m^3 or less of asphalt, plastics, cloth, paper, paints, and wood.

Some crushed aggregate do not meet the ASTM C 33 grading standards although using the proper crusher settings can provide acceptable gradings. Generally fine aggregates are coarser and more angular than required to produce workable, good quality concrete. These materials tend to produce concretes that are harsh and unworkable. It is necessary to add a finer natural sand to the recycled sand to produce concrete with suitable workability and finishability.

The water absorption of recycled aggregates is higher than for virgin aggregates due to the higher absorption of the old cement mortar that is attached the aggregate particles. The Los Angeles abrasion loss should meet the ASTM C 33 maximum (50% for general construction); all but the poorest quality recycled aggregates usually meet this limit.

ACI 555 reports that studies on strengths of concrete made with recycled coarse and natural fine aggregates have generally been 5 to 24% lower than concrete made with all virgin aggregates. Other researchers have reported that recycled aggregate concrete yields approximately the same strengths as the original concrete from which the aggregates are made. ACI 555 reported the conclusion of researchers that stated the compressive strength of concrete depends on the strength of the concrete from which it is made and is largely a function of the w/c of the concrete from which it is made and the w/c of the recycled aggregate concrete. When concrete is made with both recycled coarse and fine aggregates, the compressive strengths are generally 15 to 40% lower than for concrete made with all virgin aggregates. Blends of equal volumes of natural and recycled sand produced strengths 10 to 20% less than recycled concrete made with 100% natural sand. ACI 555 reports that Hansen found that the majority of the strength loss is brought about by the size fraction s of recycled aggregate smaller than 2 mm and for that reason the use of recycled fines may be prohibited.

The strength variability of concrete made with aggregates from different sources have greater variability than concrete made with aggregates from one source. The result is that concrete made with aggregates from recycling plants that allow unrestricted input materials will have to be designed using greater standard deviations which may increase the cost.

It has been reported that concrete made with recycled coarse and fine aggregate had reductions of the modulus of elasticity of 25 to 40%, while the reductions were 10 to 33% for concrete made with recycled coarse aggregate. Creep of concrete made with recycled aggregate has been shown to be 30 to 60% greater than for concrete made with virgin aggregates. This finding is explained by the fact that recycled aggregate concrete has up to 50% more paste volume, and creep is proportional to the amount of paste or mortar. Concrete made with all recycled aggregates have 70 to 100% greater drying shrinkage than for concrete made from all virgin material, while concrete made with recycled coarse and natural fine aggregates have 20 to 50% greater shrinkage. Concrete made from recycled aggregates with w/cs of 0.5 to 0.7 has permeabilities two to five times that of concrete made with natural aggregates..Freezing and thawing resistance has been shown in many studies to be about the same for concrete made with recycled aggregates as for concrete made with virgin aggregates. Other studies have shown that concrete made with recycled coarse and fine aggregates had much less resistance to freezing and thawing, but that if the recycled sand was replaced with natural sand, the results were similar.

Mixture proportioning is beyond the scope of this paper, but ACI 555 gives guidelines. Production of recycled aggregate concrete is similar to conventional concrete; it is recommended that recycled aggregates be presoaked and that all materials smaller than 2 mm should not be used.

What is Needed to Increase Sustainability of Aggregates?

There are several things that must be done to improve and increase sustainability of aggregates used in concrete.

1. There must be a coordinated effort by specifiers, designers and contractors to make maximum, optimum use of all aggregates produced. Local aggregates should be used whenever possible to reduce transportation costs and emissions. There is no reason to eliminate micro fines or ASR-prone aggregates in producing concrete in most cases.

2. It must be recognized that “one size fits all” does not apply to aggregates. Not all applications require high strength, high modulus, high durability concrete. Lower quality aggregates may prove to be the most economical and still provide the required properties.

3. Concrete must be engineered to use all aggregates. Mitigation of ASR can easily be accomplished using supplementary cementing materials.

4. In some cases specifications and standards may have to be changed. The long standing limit on amount of micro fines is not realistic and needs changing. A different grading standard needs to be adopted for manufactured aggregates and perhaps for recycled aggregates.

5. The public, designers, owners, specifiers and contractors must be educated on the importance of aggregates in the construction industry. Legislative bodies must understand that aggregates are the most widely used material of construction, and the future of our construction industry is heavily dependent on the ability to mine, produce and transport aggregates in and near heavily populated areas.

ACKNOWLEDGEMENTS

The contributions of Professor Tyler Lay, Oklahoma State University; Kevin Folliard, University of Texas at Austin; Fournier, Benoit; and Michael Thomas, University of New Brunswick are acknowledged in preparing the section on mitigation of ASR. Information on slides they provided were very useful in preparing the paper.

REFERENCES

Ahn, N. and Fowler, D. An Experimental Study on the Guidelines for Using Higher Contents of Aggregate Microfines in Portland Cement Concrete. *Research Report ICAR 102-1F, International Center for Aggregates Research*, 2001.

Folliard, K. J, Barborak, R., Drimalas, T., Du, L., Garber, S., Ideker, J., Ley, T., Williams, S., Juenger, M., Fournier, B., and Thomas, M. D., "Preventing ASR/DEF in New Concrete: Final Report", Technical Report 0-4085-5, Center for Transportation Research, The University of Texas, Austin, 2005 (Revised 2006), pp. 245.

Fournier, B., Chevrier, R., De Grosbois, M., Lisella, R., Folliard, K., Ideker, J., Shehata, M., Thomas, M., and Baxter, S. "The accelerated concrete prism test (60oC): variability of the test method and proposed expansion limits," Proceedings of the 12th International Conference on Alkali-Aggregate Reaction in Concrete, Beijing, China, V. 1, 2004, pp. 314-323.

Quiroga, P. N., Ahn, N., and Fowler, D. W. (2005). "Concrete Mixtures with High Microfines," *ACI Materials Journal*, 103(4), 258-264.

Quiroga, P., and Fowler, D. The Effect of Aggregate Characteristics on the Performance of Portland Cement Concrete. *ICAR Report 104,* Austin, TX, 2004.

Quiroga, P., and Fowler, D. Guidelines for Proportioning Optimized Mixtures with High Microfines. ICAR, Austin, TX, 2004.

"Removal and Reuse of Hardened Concrete," ACI 555R-01, Report of ACI Committee 555, American Concrete Institute, Detroit, MI, 2001, pp. 26.

Shehata, M. H., and Thomas, M. D. A., The effect of fly ash composition on the expansion of concrete due to alkali silica reaction, *Cement and Concrete Research* **30** (7) (2000), pp. 1063–1072.