Recyclable materials in concrete technology: sustainability and durability

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ABSTRACT: A judicious use of natural resources, achieved by the use of by-products and recyclable materials, and a lower environmental impact, achieved through reduced carbon dioxide emission and reduced natural aggregate extraction from quarries; represent two main actions that meet the needs for sustainable construction development. Recycled-aggregate concrete containing fly ash is an example of construction material in harmony with this concept, whereby sustainable construction development is feasible with satisfactory performance, in terms of both safety and serviceability of structures, at lower costs and with environmental advantages over ordinary concrete. In this paper, criteria are discussed on the basis of which the use of by-products and recyclable materials in concrete can be optimized. Fresh concrete behaviour during placing is also discussed. Moreover, when using recycled materials appropriately, some important properties of the hardened concrete such as ductility and durability can be better engineered, as this paper explains and emphasizes.

1 INTRODUCTION

Concrete is basically made of aggregates glued by a cementitious materials paste, which is made of cementitious materials and water. Each one of these concrete primary constituents, to a different extent, has an environmental impact and gives rise to different sustainability issues [Mehta 2001, 2002].

The current concrete construction practice is thought unsustainable because, not only it is consuming enormous quantities of stone, sand, and drinking water, but also two billion tons a year of portland cement, which is not an environment-friendly material from the standpoint of energy consumption and release of green-house gases (GHG) leading to global warming. Furthermore, the resource productivity of portland-cement concrete products is much lower than expected because they crack readily and deteriorate fast. Since global warming has emerged as the most serious environmental issue of our time and since sustainability is becoming an important issue of economic and political debates, the next developments to watch in the concrete industry will not be the new types of concrete, manufactured with expensive materials and special methods, but low cost and highly durable concrete mixtures containing largest possible amounts of industrial and urban by-products that are suitable for partial replacement of portland cement, virgin aggregate, and drinking water [Mehta 2004].

According to this new vision, notwithstanding the energy consumption of cement production and the related carbon dioxide emissions, concrete can “adsorb” these negative effects and become an environmentally sustainable material. This outstanding effect is mainly attributable to the opportunity of easily incorporating mineral additions in concrete. Such mineral additions are quite different in nature, composition, and origin. Thanks to concrete technology developments, particularly connected to advances in concrete admixtures, mineral additions are used quite frequently in concrete today. In fact, many by-products and solid recyclable materials can be used in concrete mixtures as aggregates or cement replacement, depending on their chemical and physical characterization. The capacity of concrete for incorporating these secondary raw materials is very wide and the main limit is their availability, which has to be comparable with the cement stream, since it is not worthwhile to develop new cementitious materials if their availability on the market cannot be guaranteed. Focus is being shifted on developments in concrete technology that are already underway and are revolutionary in the sense that the goal is not a special concrete type meeting a particular engineering need. Instead, the goal is to transform all concrete into a general-purpose building material that is composed of eco-friendly components, and produce crack-free and highly durable structures [Mehta 2004].

The above described methods will undoubtedly improve the technological sustainability of concrete as a construction material. However, to move toward ecological sustainability, we must achieve radical improvements in our resource productivity by reducing drastically the wasteful consumption of materials. This means that the long-term solution to the problem of sustainability of modern construction materials lies in dramatically improving their durability, by applying the "making do with less" approach. Otherwise, if the construction industry and society continue with the business-as-usual approach, it will reach the threshold point at which the natural support systems are irreversibly damaged [Mehta 2004].

Indeed, the science and technology to achieve a quantum jump in durability of concrete, in a cost-effective way, is available to today's concrete technologists. It is necessary to take a preventive, rather than a remedial approach [Mehta 2001]. Modern reinforced concrete structures begin to deteriorate in 10 to 20 years or even less in some environments primarily because portland-cement concrete is highly crack-prone and, therefore, become permeable during service. In permeable concrete the embedded steel reinforcement corrodes readily which results in progressive deterioration of the structure. Today's construction practice, driven by a culture of ever-accelerating construction speed, requires concrete mixtures containing a relatively large amount of high-early strength portland cement. As a result, the crack resistance of modern concrete is poorer than necessary due to high tensile stresses generated by a combination of high thermal and drying shrinkage strains, and too little stress relaxation from creep. Clearly, if durability and sustainability are now the important goals of the industry, then the current construction practice must undergo a paradigm shift from faster speeds of construction and less durable concrete to a construction practice that would produce crack-free structures [Mehta 2001, 2004].

As an example, environmental issues associated with carbon dioxide emissions from the production of portland cement demand that supplementary cementing materials in general, and fly ash as well as ground granulated blast-furnace slag in particular, be used in increasing quantities to replace the portland cement in concrete. Given the almost unlimited supply of good quality fly ash worldwide, new concrete technology such as high-volume fly ash concrete has been developed, based on the combined use of superplasticizers and supplementary cementing materials, leading to economical high-performance, crack-resistant concrete with enhanced durability [Malhotra 1986, 1999, 2003, Mehta 1999, Malhotra & Mehta 2002].

Therefore, much of the discussion of the sustainability of the concrete industry to date has dealt with materials issues such as the use of portland cement replacement materials and recycling of concrete removed from existing structures. However, any discussion of the sustainability of the concrete industry must consider industry concerns much broader than those of "greenness" of a given technology. For example, if the public or designers perceive concrete as a non-durable material or as a material that is more difficult to design with, the sustainability of the industry is affected [Holland 2002]. A related comment is that public funding has become a very limited resource with many demands running after limited discretionary funding. As a result, publicly funded infrastructure simply must last longer, since the replacement of these structures before a reasonable life span cannot be allowed.

In general, there is an increased interest in durability of structures and life-cycle cost. Projects have recently been completed where 1,000 year service life for the concrete has been requested and achieved through high-performance, high-volume fly ash concrete [Mehta & Langley 2000]. While these projects are unusual, service life requirements for 100 years for bridges in severe environments are becoming more common [Holland 2002].

Finally, it must be realized, and time and again stressed, that resources are limited. In particular, the mineral resources that are necessary for cement and concrete production are being stretched or exhausted in some locations. Yet in spite of the growing awareness that resources are being depleted, there is a resistance against developing new sources [Holland 2002].

Recently published reports [Corinaldesi & Moriconi 2001, Moriconi et al. 2003, Moriconi

2005b, Corinaldesi & Moriconi 2006] show that the goal of complete utilization of construction and demolition wastes is attainable. For instance, it has been found [Moriconi et al. 2003] that the finely ground fraction from these wastes, when used as a partial replacement for cement, improves the bond strength between mortar and fired-clay brick in masonry units. For use in structural concrete mixtures, it was shown [Corinaldesi & Moriconi 2001] that the strength loss resulting from complete replacement of natural coarse and fine aggregates with recycled-concrete aggregates can be compensated by incorporation of fly ash and water-reducing chemical admixtures into the new fresh concrete mixture.

This paper is a review of the research work done in the last few years in order to promote recycling into concrete for common use in building construction [Naik & Moriconi 2005], with the aim of emphasizing the feasibility, as well as the advisability, of such an action, meeting at the same time sustainability and durability. Four significant and demonstrative examples are described below.

2 RECYCLED-AGGREGATE CONCRETE

2.1 *Feasibility and sustainability*

Recycled-aggregate concrete (RAC) for structural use can be prepared by completely substituting natural aggregate, in order to achieve the same strength class as the reference concrete, manufactured by using only natural aggregates [Corinaldesi et al. 1999]. This is obviously a provocation, since a large stream of recycled aggregates to allow for full substitution of natural aggregates is not available. However, it is useful to prove that to manufacture structural concrete by partly substituting natural with recycled aggregates by up to fifty percent is indeed feasible. In any case, if the adoption of a very low water to cement ratio implies unsustainably high amounts of cement in the concrete mixture, recycled-aggregate concrete may also be manufactured by using a water-reducing admixture in order to lower both water and cement dosage, or even by adding fly ash as a partial fine aggregate replacement and by using a superplasticizer to achieve the required workability [Corinaldesi & Moriconi 2001].

Moreover, high-volume fly ash recycled-aggregate concrete (HVFA-RAC) can be manufactured with a water to cement ratio of 0.60, by simultaneously adding to the mixture as much fly ash as cement, and substituting the fine aggregate fraction [Corinaldesi & Moriconi 2002]. Thus, water to cementitious material (binder) ratio of 0.30 is obtained enabling the concrete to reach the required strength class (Table 1). This procedure is essential for designing an environmentally-friendly concrete. All the concretes can be prepared maintaining the same fluid consistency by proper addition of an appropriate class of a superplasticizer.

Table 1. Concrete mixture proportions (kg/m^3).

Concrete mixture		NAC	RAC	HVFA-RAC
Water		230	230	230
Cement		380	760	380
Fly ash		-	-	380
Natural sand		314	-	-
Fine recycled fraction		-	-	-
Crushed aggregate		1338	-	-
Coarse recycled fraction		-	1169	1057
Superplasticizer		-	-	6.8
Water/Cement		0.60	0.30	0.60
Water/Binder		0.60	0.30	0.30
Compressive	3	16	26	20
strength (MPa)	28	27	31	29
at days:	60	32	34	36

2.2 *Technical improvement*

When concrete shows high fluidity, in addition to good cohesiveness, it is said to be self-compacting. This recent achievement of concrete technology, which has lead to several advantages, is in fact a development of the well-known rheo-plastic concrete [Collepardi 1976, 2001, 2003], achieved with superplasticizers, in which segregation and bleeding are suppressed by a filler addition and the use of a viscosity-modifying agent. However, these additions may not be sufficient, if the maximum volume of coarse aggregate and minimum volume of fine particles (including cement, fly ash, ground limestone, and other similar materials) are not complied with. Furthermore, from rheological tests on cement pastes, it has been observed that, for maximum segregation resistance, the yield stress of the paste should be high [Billberg 1999, Emborg 1999, Saak et al. 1999, 2001] and the difference in density between the aggregate and the paste should be low. This would mean that segregation will be particularly reduced when lighter aggregate, such as recycled aggregate, is used [Corinaldesi & Moriconi 2004]. Moreover, this behaviour seems to be enhanced when concrete-rubble powder, that is the fine fraction produced during the recycling process of concrete-rubble to make aggregates, is reused as filler. In this condition, the segregation resistance appears so high that the coarse recycled aggregate can float on a highly viscous cement paste, and an adjustment could be attempted by adding fly ash which, when used alone as a filler, confers reduced flow-segregation resistance and increased flowability to concrete.

2.3 *Durability*

Aspects related to the durability of recycled-aggregate concretes have already been studied. In particular, attention has been focused on the influence of concrete porosity on drying shrinkage and corrosion of embedded steel bars as well as on concrete carbonation, chloride ion penetration, and concrete resistance to freezing and thawing cycles [Corinaldesi & Moriconi 2002, Tittarelli & Moriconi 2002, Corinaldesi et al. 2001, 2002b, Moriconi 2003]. Results showed that, when fly ash is added to recycled-aggregate concrete:

1. the pore structure is improved, and particularly the macropore volume is reduced causing benefits in terms of mechanical performance, such as compressive, tensile and bond strength [Corinaldesi & Moriconi 2002, Moriconi 2003]. With respect to ordinary concrete prepared with natural aggregate, the only difference is a somewhat reduced stiffness of recycled-aggregate concrete containing fly ash, which should be taken into account during structural design [Moriconi 2003];
2. the drying shrinkage of recycled-aggregate concrete, from a serviceability point of view, does not appear to be a problem since, due to the reduced stiffness of this concrete, the same risk of crack formation results as for ordinary concrete under restrained conditions [Moriconi 2003];
3. testing of concrete resistance against freezing and thawing cycles showed no difference between natural-aggregate concrete and high-volume fly ash recycled-aggregate concretes [Corinaldesi & Moriconi 2002];
4. the addition of fly ash is very effective in reducing carbonation and chloride ion penetration depths in concrete (Figs 1, 2), because of pore refinement of the cementitious matrix due to a filler effect and pozzolanic activity of fly ash. Moreover, the strong beneficial effect of the presence of fly ash on chloride penetration depth is quite evident since the chloride ion diffusion coefficient in high-volume fly ash concrete is one order of magnitude less than that into concrete without a fly ash addition [Corinaldesi & Moriconi 2002, Corinaldesi et al. 2002];

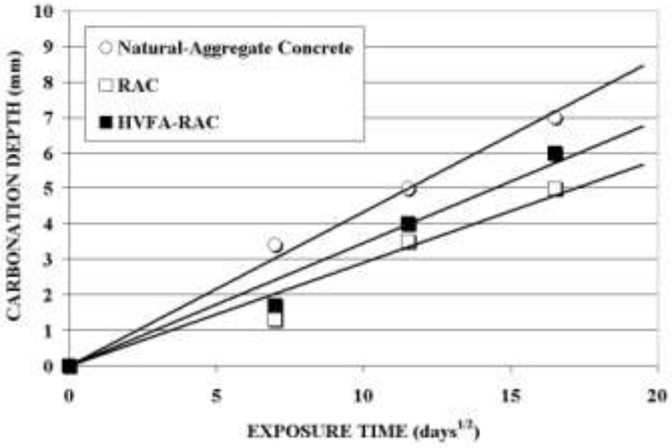

Figure 1. Carbonation depth as a function of the time of exposure to air.

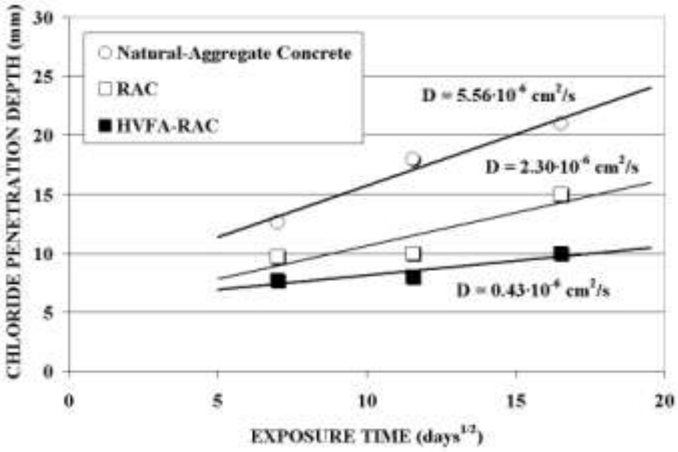

Figure 2. Chloride penetration depth as a function of the time of exposure to a 10% sodium chloride aqueous solution.

5. as far as corrosion aspects are concerned, the use of fly ash does not decrease the corrosion resistance of steel reinforcement (Fig. 3), as long as the concrete strength is adequate, whilst it appears very effective in protecting galvanized steel reinforcement (in Fig. 4 the zinc layer is totally consumed only for natural-aggregate

concrete) in porous concrete, as it can occur when recycled aggregates are used, even in the case of cracked concrete [Corinaldesi et al. 2002, Moriconi 2003];

Figure 3. Visual observation of the corrosive attack at the crack apex on bare steel plates embedded in natural-aggregate concrete (above), RAC (middle) and HVFA concrete (below).

6. in general, it is confirmed that concrete containing high volume of fly ash does not present a problem with respect to corrosion of reinforcement, because of the very low permeability of concrete, even when a porous aggregate, such as recycled aggregate, is used. In fact, if on the one hand fly ash addition reduces the concrete pore solution alkalinity by altering the passivity conditions of steel reinforcement, on the other hand it improves significantly the concrete microstructure by making the penetration of aggressive agents and the onset of corrosion increasingly difficult [Moriconi 2005a].

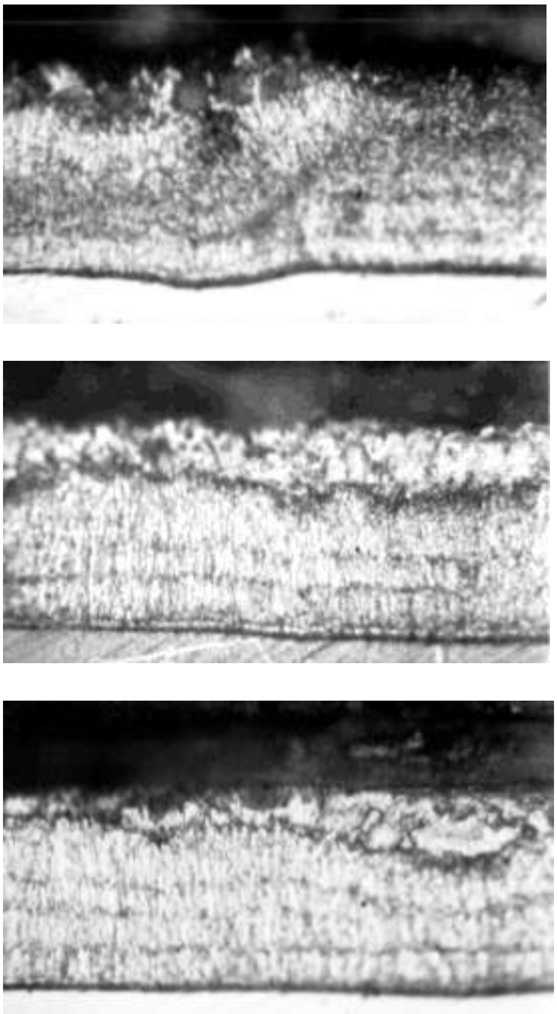

Figure 4. Metallographic cross section of galvanized steel plates embedded in cracked natural-aggregate concrete (above), RAC (middle) and HVFA concrete (below).

2.4 *Economical evaluation*

As in most common structural applications, if a strength class value of 30 MPa is required, recycled-aggregate concrete without any mineral addition may not perform satisfactorily, whereas recycled-aggregate concrete with high-volume fly ash would have excellent performance. For this reason an economical comparison should be made for comparable performances [Corinaldesi & Moriconi 2001] between natural-aggregate concrete and recycled-aggregate concrete with high-volume fly ash of the same strength class.

Table 2. Traditional (T) and eco-balanced* (E-B) costs referred to one m^3 of concrete.

Ingredient	Unit cost (€/kg)	Natural-aggregate concrete		RAC		HVFA-RAC	
		T	E-B	T	E-B	T	E-B
Water	0.001	0.30	0.30	0.30	0.30	0.30	0.30
Cement	0.121	45.98	45.98	91.96	91.96	45.98	45.98
Fly ash	0.022	-	-	-	-	8.36	8.36
Fly ash disposal	0.250	-	-	-	-	-	-95.00
Natural sand	0.015	4.55	4.55	-	-	-	-
Fine recycled fraction	0.007	-	-	-	-	-	-
Crushed aggregate	0.013	17.26	17.26	-	-	-	-
Coarse recycled fraction	0.006	-	-	7.54	7.54	6.82	6.82
Rubble disposal	0.050	-	-	-	-58.45	-	-52.85
Superplasticizer	1.435	-	-	-	-	9.76	9.76
Total		68.09	> 68.09	99.80	41.35	71.22	-76.63

* Only negative eco-costs, deriving from waste disposal, are taken into account. Expenses related to the environmental impact caused by the extraction of natural aggregates from quarries should be added to the eco-balanced cost of natural-aggregate concrete.

On the basis of current costs of the individual constituents in Italy, traditional costs evaluation can be carried out leading to the cost of high-volume fly ash recycled-aggregate concrete being slightly higher (about 5%) than natural-aggregate concrete (Table 2). This result is nearly obvious since both types of concrete belong to the same strength class.

However, besides the traditional cost of aggregates, it would be important to take into account their environmental cost. The *eco-costs* [Tazawa 1999], which are the expenses necessary to eliminate the environmental impact caused by the extraction of natural aggregates from quarries, should be considered as well as the *negative eco-costs*, that are the expenses to eliminate the environmental load if rubble from building demolition, and also fly ash from thermal plants, are not utilized to produce concrete. By considering the environmental costs of aggregates [Tazawa 1999], though not yet easily determinable and changeable with social and political factors, it can be predicted that high-volume fly ash recycled-aggregate concrete in the future could be remarkably cheaper than the natural-aggregate concrete.

3 RECYCLED-AGGREGATE MORTARS

3.1 *Feasibility and sustainability*

As shown by several authors [Kasai 1988, Hansen 1992, Dhir et al. 1998], the presence of masonry in concrete rubble is particularly detrimental to the mechanical performance and durability of recycled-aggregate concrete, and the same negative effect is detectable when natural sand is replaced by fine recycled-aggregate fraction. These strength losses can be counteracted by adopting appropriate measures, such as the reduction of water to cement ratio and the addition of mineral admixtures [Corinaldesi & Moriconi 2001]. However, all these actions lead to reduced use of fine recycled material, which turns out to be only partially employable in concrete.

An alternative use of both masonry rubble and surplus fine recycled material could be in mortars. These could contain either recycled instead of natural sand, or powder obtained by brick grinding, as partial cement substitution. Both attempts were carried out within an experimental activity [Corinaldesi et al. 2002a].

Table 3. Mortar mixture proportions and compressive strength.

Mixture	W/CM	Mixture proportions, kg/m^3					Compressive strength, MPa		
		Water	Cement	Natural sand	Recycled aggregate	Brick powder	7 days	14 days	28 days
Ref	0.50	225	450	1350	-	-	48	58	61
BP	0.50	250	315	1350	-	135	30	33	36
RA	0.67	300	450	-	1350	-	28	32	38

Several mortars were prepared. The proportions of their mixtures are given in Table 3. The cement to sand ratio was 1:3 (by mass); the water content of each mortar was set to achieve the same consistency of 110 ± 5 mm, evaluated according to EN 1015-3. When recycled sand (RA) was used, a higher water dosage was necessary to achieve the same consistency as that of the other mortars, because of the higher water absorption of the recycled sand with respect to the natural sand.

3.2 *Technical improvement and durability*

Prismatic specimens (40 x 40 x 160 mm) were prepared, cast, and wet cured at 20°C. The compressive strength was evaluated according to EN 196-1. The results obtained are reported in Table 3. Mortars containing brick powder (BP) and recycled aggregate (RA) had significantly lower compressive strengths with respect to the reference cementitious mortar (Ref).

In order to evaluate the bond strength developed during the shearing of a brick with respect to another brick along a mortar layer 10 mm thick, a test method, derived from the draft European Standard prEN 1052-3 [UNI EN 1052-3: 2003], was adopted. In this procedure the masonry behavior in the absence of normal stress was investigated, corresponding to the constant term in the Mohr-Coulomb friction law.

The tested model, shown in Figure 5, is composed of three bricks; it has a symmetric structure thus avoiding eccentric loads. The applied load (L) was measured and at the same time the vertical displacement of the central brick (δ) was monitored. Usually at the end of the test only one joint cracked, so the bond strength was calculated dividing the maximum load by twice the fracture area where brick and mortar were in contact (approximately 120 x 200 mm). Test results are shown in Figure 5. In particular, very high bond strength was obtained by coupling red bricks and recycled-aggregate mortar (RA) [Corinaldesi et al. 2002a, Moriconi et al. 2003].

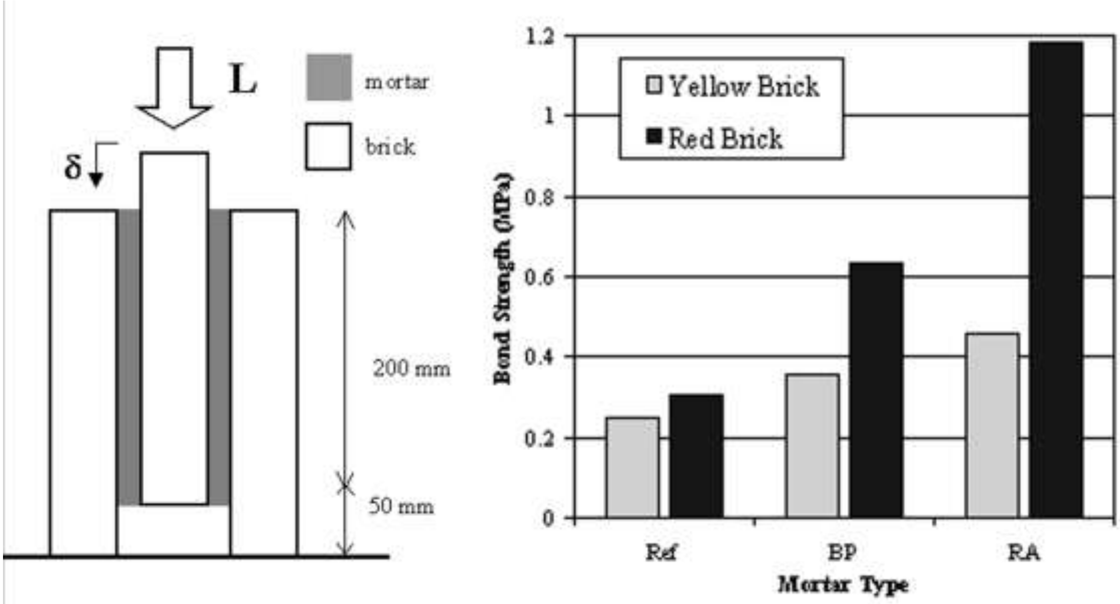

Figure 5. Masonry model and maximum values of the mortar-brick bond strength.

In general, experimental results showed the feasibility of using either recycled instead of natural sand as an aggregate, or powder obtained by grinding bricks, as partial cement substitution for the production of mortars. In this way, the alternative use of undesirable fractions of the recycled aggregate in the production of mortar had the added effect of improving the quality of the recycled aggregate for the production of concrete. Moreover, in the case that a high masonry resistance to external actions is one of the design requirements, these mortars, in particular those containing recycled aggregate could be of benefit in terms of mechanical performance and hence durability.

4 SELF-COMPACTING CONCRETE CONTAINING RUBBLE POWDER

4.1 *Feasibility and sustainability*

A further experimental step was carried out concerning self-compacting concrete [Corinaldesi et al. 2005a]. In fact, not only the concrete-rubble from building demolition, after a suitable treatment, can be reused as aggregates for new concretes but also the dust produced during their processing could be, in turn, utilized as filler for manufacturing self-compacting concrete. However, this dust proved to be detrimental for the mechanical performance of the recycled-aggregate concrete due to its high water absorption and the possibility of reducing the dust content in recycled-aggregate fractions allowed improvement of their quality.

The mixture proportions of two self-compacting concretes are reported in Table 4. Both concretes were prepared with the same water to cement ratio of 0.45. In order to optimize the grain size distribution of the solid particles in the concrete, the fine and the coarse aggregate fractions were combined at 28% and 72% by volume, respectively, taking into account also the suggestions reported in the literature concerning the mixture proportion of self-compacting concrete [Bui & Montgomery 1999, Jacobs & Hunkeler 1999].

In order to achieve a volume of very fine particles of about 190 l/m^3, it was necessary to use a mineral addition besides cement, at a dosage of either 100 kg (concrete-rubble powder) or 120 kg (limestone powder), depending on their volume mass. The limestone powder used was obtained as a by-product of marble working [Corinaldesi et al. 2005a]. Its Blaine fineness was 0.59 m^2/g and its specific gravity was 2.65 kg/m^3. Alternatively, a powder obtained from the recycling process of rubble from building demolition was added. This process mainly consisted of crushing concrete and masonry waste and collecting the material passing through the sieve ASTM n° 170 of 90 μm. This rubble powder had a Blaine fineness of 0.99 m^2/g and a specific gravity of 2.15 kg/m^3.

Table 4. Self-compacting concrete mixture proportions.

Mixture	SCC+LP	SCC+RP
W/C	0.45	0.45
W/CM	0.36	0.37
Mixture proportions, kg/m^3		
Water	200	200
Cement	440	440
Limestone Powder	120	-
Rubble Powder	-	100
Natural Sand	1110	1110
Crushed Aggregate	430	430
Superplasticizer	4.4	5.3

An acrylic-based superplasticizer was employed at a dosage of 1.0% and 1.2%, respectively for the cases of limestone powder or rubble powder addition, due to their different fineness.

4.2 *Technical improvement and durability*

As a first step, properties of the fresh concrete other than slump were evaluated, since in this case the slump value is not relevant due to the very fluid character of the concrete. Therefore, the attention was focused on the measurement of the slump flow and on the L-box test with horizontal steel bars.

Compression tests according to Italian Standards UNI 6132-72 were carried out on cubic specimens, which were tested at right angles to the position of casting.

The results obtained in terms of both fresh and hardened concrete performances are reported in Table 5.

In relation to the slump flow test, both concretes showed enough fluidity to be self-compactable; but a certain flow-segregation, with the presence of a halo of cement paste around the slumped concrete, was observed for the ‘SCC+LP’ concrete while the ‘SCC+RP’ concrete seemed to behave as a quite viscous system.

Table 5. Performances of the fresh and hardened self-compacting concretes.

Mixture		SCC+LP	SCC+RP
Slump flow test	Φ_{fin} * (mm)	750	700
	t_{500} ** (s)	1	4
	t_{fin} *** (s)	1	11
L-box test	ΔH_{fin} **** (mm)	30	65
	t_{edge} ***** (s)	5	1
	t_{stop} ****** (s)	12	6
Compressive strength (MPa)	curing time (days): 1	17.0	17.4
	3	25.4	27.8
	7	32.1	32.9
	28	40.1	40.9

* mean diameter of the slumped concrete;
** elapsed time to gain the mean diameter of 500 mm;
*** elapsed time to gain the final configuration;
**** difference in the concrete level in the opposite ends of the box;
***** elapsed time to reach the opposite edge of the box;
****** elapsed time to establish the final configuration.

In relation to the L-box test, both concretes showed good results in terms of mobility through narrow sections. Concerning the flow-segregation, a certain separation between the coarse aggregate particles and the surrounding cement paste was observed only in the case of the ‘SCC+LP’ concrete.

In terms of mechanical performance, the concretes prepared with either limestone powder or concrete-rubble powder performed similarly, with a 28-day compressive strength of about 40 MPa.

Concrete-rubble powder proved to be effective when added to self-compacting concrete mixture and its reuse can be advantageous from an environmental point of view since it is constituted by the dust produced during recycled aggregate processing.

5 REUSE OF GRP INDUSTRIAL WASTE IN CEMENTITIOUS PRODUCTS

5.1 *Feasibility, sustainability and durability aspects*

Glass Reinforced Plastic (GRP) is a composite material made of glass fibres dispersed in a resin, usually polyester, widely used in several fields from buildings to furniture to boats. Every year, in Western Europe, GRP processing produces 40000 tons of industrial waste. In Italy this waste is disposed in landfill, due to the difficulty of separating the glassy part from the polymeric matrix. Concrete made with recycled glass [Shao et al. 2000, Dyer & Dhir 2001, Ambrosie & Pera 2003, Quian et al. 2003, Corinaldesi et al. 2005b] or polymeric addition [Zhao 1995] has already been proposed in the literature. In particular, the polyester concrete is particularly resistant to chemical agents as well as to thermal cycles and can be useful for light weight constructions [Zhao 1995]. Therefore, the feasibility of re-using GRP industrial waste coming from a shipyard in order to manufacture concrete elements has been considered [Tittarelli & Moriconi 2005].

The finest GRP waste was physically and chemically characterized in order to outline compatibility issues with cement, if any. By taking into account its particle size distribution, the feasibility of using this waste as a partial cement replacement to produce new GRP blended cements was considered. Since this type of addition is not included in the European Standard on cements, the effect of GRP addition on the properties of fresh and hardened standard mortars was evaluated. Then the durability in terms of porosity, water absorption, and drying shrinkage of precast elements made with the GRP blended cements was investigated.

The chemical and physical characterization of the GRP industrial waste powder showed its compatibility with cement. Mechanical strength threshold acceptable by actual cement standards could be assured by replacing up to 15% of cement with GRP. The “GRP cements”, even if they show lower mechanical strengths, could confer lightness and some deformability to cementitious products manufactured with them. Mortars manufactured by using these cements were more porous with respect to the reference mortar without GRP, due to higher water to cement ratio and due to the absence of any binding capacity of GRP. Nevertheless, their capillary water absorption and drying shrinkage were lower than that of the reference mortar without GRP.

These results demonstrated the potential of re-using an abundant industrial by-product, at present landfilled, to manufacture durable precast concrete elements.

6 CONCLUSIONS

Against a wide availability of rubble from building demolition to be recycled, several fields of employment other than roadbeds or floor foundations have been examined in the experimental activity.

Recycled-aggregate fractions up to 15 mm, although containing masonry rubble up to 25 to 30%, proved to be suitable for manufacturing structural concrete even when employed as a total substitution of the fine and coarse natural aggregate fractions.

The most important conclusion drawn appears to be that the compressive strength of the recycled-aggregate concrete can be improved to equal or even exceed that of natural-aggregate concrete by adding fly ash to the mixture as a fine aggregate replacement. In this way, a given strength class value, as required for a wide range of common uses, can be reached through both natural-aggregate concrete and recycled-aggregate concrete with fly ash, by adequately decreasing the water to cement ratio with the aid of a superplasticizer in order to maintain the workability.

Concrete manufactured by using recycled aggregate and fly ash shows no deleterious effect on the durability of reinforced concrete, with some improvement for some cases.

From an economical point of view, if only the traditional costs are taken into account, recycled-aggregate concrete with fly ash could be less attractive than natural-aggregate concrete. However, if the eco-balanced costs are considered, the exact opposite would be valid.

Moreover, the fine fraction with particle size up to 5 mm, when reused as aggregate for mortars, allowed excellent bond strengths between mortar and bricks, in spite of a lower mechanical performance of the mortar itself. Also the masonry-rubble can be profitably treated and reused for preparing mortars.

Even for the fine fraction produced during the recycling process, that is the concrete-rubble powder, an excellent reuse was found, as filler in self-compacting concrete.

The attempt to improve the quality of the recycled aggregates for new concretes by reusing in different ways the most detrimental fractions, i.e., the material coming from masonry rubble and the finest recycled materials, allowed to achieve surprising and unexpected performances for mortars and self-compacting concretes.

Other industrial wastes, such as GRP waste powder, can prove useful to be re-used in cementitious products, by improving some durability aspects.

REFERENCES

Ambroise, J. & Pera, J. 2003. Durability of glass-fibre cement composites – comparison between normal Portland and Calcium Sulfoaluminate cements, *ACI Award Presentation at the Sixth CANMET/ACI International Conference on Durability of Concrete, Thessaloniki, Greece, 6 June 2003*.

Billberg, P. 1999. Fine mortar rheology in mix design of SCC, In A. Skarendahl & O. Petersson (eds.), *Self-Compacting Concrete, Proc. first RILEM intern. symp., Stockholm, Sweden*, 47-58.

Bui, V.K. & Montgomery, D. 1999. Mixture Proportioning Method for Self-compacting High Performance Concrete with Minimum Paste Volume, In A. Skarendahl & O. Petersson (eds.), *Self-Compacting Concrete, Proc. first RILEM intern. symp., Stockholm, Sweden*, 373-384.

Collepardi, M. 1976. Assessment of the “rheoplasticity” of concrete, *Cement and Concrete Research*, 6: 401-408.

Collepardi, M. 2001. A very close precursor of self-compacting concrete (SCC), In *Sustainable development of cement and concrete, Proc. three-day CANMET/ACI intern. symp., San Francisco, CA, USA, 16-19 September 2001*, Supplementary Papers: 431-450.

Collepardi, M. 2003. Self-compacting concrete: What is new?, In V.M. Malhotra (ed.), *Superplasticizers and other chemical admixtures in concrete, Proc. seventh CANMET/ACI intern.*

conf., Berlin, Germany, 20-23 October 2003, Publication SP-217: 1-16. Farmington Hills, MI, USA: American Concrete Institute.

Corinaldesi, V., Giuggiolini, M., & Moriconi, G. 2002a. Use of rubble from building demolition in mortars, *Waste Management*, 22(8): 893-899.

Corinaldesi, V., Gnappi, G., Moriconi, G., & Montenero, A. 2005. Reuse of ground waste glass as aggregate for mortars, *Waste Management*, 25(2): 197-201.

Corinaldesi, V., Isolani, L., & Moriconi, G. 1999. Use of rubble from building demolition as aggregates for structural concretes, In M. Pelino (ed.), *Valorisation and recycling of industrial wastes, Proc. 2nd nat. congr., L'Aquila, Italy, 5-8 July 1999*, 145-153.

Corinaldesi, V. & Moriconi, G. 2001. Role of chemical and mineral admixtures on performance and economics of recycled-aggregate concrete, In V.M. Malhotra (ed.), *Fly ash, silica fume, slag and natural pozzolans in concrete, Proc. seventh CANMET/ACI intern. conf., Madras, India, 22-27 July 2001*, Publication SP-199: 869-884. Farmington Hills, MI, USA: American Concrete Institute.

Corinaldesi, V. & Moriconi, G. 2002. Durability of recycled-aggregate concrete incorporating high volume of fly ash, In *Durability of building materials and components, Proc. 9th intern. conf., Brisbane, Queensland, Australia, 17-20 March 2002*, Paper 71.

Corinaldesi, V. & Moriconi, G. 2004. The role of recycled aggregates in self-compacting concrete, In V.M. Malhotra (ed.), *Fly ash, silica fume, slag and natural pozzolans in concrete, Proc. eighth CANMET/ACI intern. conf., Las Vegas, NV, USA, 23-29 May 2004*, Publication SP-221: 941-955. Farmington Hills, MI, USA: American Concrete Institute.

Corinaldesi, V. & Moriconi, G. 2006. Behavior of beam-column joints made of sustainable concrete under cyclic loading, *Journal of Materials in Civil Engineering*, 18(5): 650-658.

Corinaldesi V., Moriconi G., & Naik T.R. 2005. Characterization of marble powder for its use in mortar and concrete, In V.M. Malhotra & K. Sakai (eds.), *Sustainable development of cement, concrete and concrete structures, Proc. three-day intern. symp., Toronto, Canada, 5-7 October 2005*, 313-336.

Corinaldesi, V., Moriconi, G., & Tittarelli, F. 2002b. Sustainable and durable reinforced concrete construction, In V.M. Malhotra (ed.), Innovations in design with emphasis on seismic, wind and environmental loading, quality control and innovations in materials/hot-weather concreting, Proc. ACI fifth intern. conf., Cancun, Mexico, 10-13 December 2002, Publication SP-209: 169-186. Farmington Hills, MI, USA: American Concrete Institute.

Corinaldesi, V., Tittarelli, F., Coppola, L., & Moriconi, G. 2001. Feasibility and performance of recycled aggregate in concrete containing fly ash for sustainable buildings, In V.M. Malhotra (ed.), *Sustainable development of cement and concrete, Proc. three-day CANMET/ACI intern. symp., San Francisco, CA, USA, 16-19 September 2001*, Publication SP-202: 161-180. Farmington Hills, MI, USA: American Concrete Institute.

Dhir, R.K., Henderson, N.A., & Limbachiya, M.C. (eds.) 1998. *Use of Recycled Concrete Aggregate*. London, UK: Thomas Telford.

Dyer, T.D. & Dhir, K.R. 2001. Chemical reactions of glass cullet used as cement component, *Journal of Materials in Civil Engineering*, 13(6): 412-417.

Emborg, M. 1999. Rheology tests for self-compacting concrete – How useful are they for the design of concrete mix for full scale production?, In A. Skarendahl & O. Petersson (eds.), *Self-Compacting Concrete, Proc. first intern. RILEM symp., Stockholm, Sweden, 13-15 September 1999*, 95-105.

Holland, T.C. 2002. Sustainability of the concrete industry – What should be ACI's role?, *Concrete International*, 24(7): 35-40.

Hansen, T.C. (ed.) 1992. *Recycling of demolished concrete and masonry*. London, UK: E & FN Spon.

Jacobs, F. & Hunkeler, F. 1999. Design of self-compacting concrete for durable concrete structures, In A. Skarendahl & O. Petersson (eds.), *Self-Compacting Concrete, Proc. first intern. RILEM symp., Stockholm, Sweden, 13-15 September 1999*, 397-407.

Kasai, Y. (ed.) 1988. *Demolition and reuse of concrete and masonry. Reuse of demolition waste*. Volume Two. London, UK: Chapman & Hall.

Malhotra, V.M. 1986. Superplasticized fly ash concrete for structural applications, *Concrete International*, 8(12): 28-31.

Malhotra, V.M. 1999. Making concrete 'greener' with fly ash, *Concrete International*, 21(5): 61-66.

Malhotra, V.M. 2003. Concrete technology for sustainable development, In *Sustainable development in cement and concrete industries, Proc. two-day intern. seminar, Milan, Italy, 17-18 October 2003*, 11-18.

Malhotra, V.M. & Mehta, P.K. (eds.) 2002. *High-performance, high-volume fly ash concrete: materials, mixture proportioning, properties, construction practice, and case histories*. Ottawa, Canada: Supplementary Cementing Materials for Sustainable Developments Inc..

Mehta, P.K. 1999. Concrete technology for sustainable development, *Concrete International*, 21(11): 47-53.

Mehta, P.K. 2001. Reducing the environmental impact of concrete, *Concrete International*, 23(10): 61-66.

Mehta, P.K. 2002. Greening of the concrete industry for sustainable development, *Concrete International*, 24(7): 23-28.

Mehta, P.K. 2004. The next revolution in materials of construction, *Proc. VII AIMAT congr., Ancona, Italy, 29 June – 2 July 2004*, Keynote Paper 1.

Mehta, P.K. & Langley, W.S. 2000. Monolith foundation: built to last '1000 years', *Concrete International*, 22(7): 27-32.

Moriconi, G. 2003. Third millennium concrete: a sustainable and durable material, *L'Industria Italiana del Cemento*, 787: 430-441.

Moriconi, G. 2005b. Reinforcement corrosion experience with concrete mixtures containing fly ash, In N. Bhanumathidas & N. Kalidas (eds.), *Concrete Technology for Sustainable Development with Emphasis on Infrastructure, Proc. second intern. symp., Hyderabad, India, 27 February – 3 March 2005*, 69-81.

Moriconi G., 2005a. Aggregate from recycled concrete and demolition wastes, In N. Bhanumathidas & N. Kalidas (eds.), *Concrete Technology for Sustainable Development with Emphasis on Infrastructure, Proc. second intern. symp., Hyderabad, India, 27 February – 3 March 2005*, 543-555.

Moriconi, G., Corinaldesi, V., & Antonucci, R. 2003. Environmental-friendly mortars: a way to improve bond between mortar and brick, *Materials and Structures*, 36(264): 702-708.

Naik, T.R. & Moriconi, G. 2005. Environmental-friendly durable concrete made with recycled materials for sustainable concrete construction, In V.M. Malhotra & K. Sakai (eds.), *Sustainable development of cement, concrete and concrete structures, Proc. three-day intern. symp., Toronto, Canada, 5-7 October 2005*, 485-505.

Quian, X., Shen, B., Mu, B., & Li, Z. 2003. Enhancement of aging resistance of glass fiber reinforced cement, *Materials and Structures*, 36(259): 323-329.

Saak, A.W., Jennings, H.M., & Shah, S.P. 1999. Characterization of the rheological properties of cement paste for use in self-compacting concrete, In A. Skarendahl & O. Petersson (eds.), *Self-Compacting Concrete, Proc. first RILEM intern. symp., Stockholm, Sweden*, 83-93.

Saak, A.W., Jennings, H.M., & Shah, S.P. 2001. New methodology for designing self-compacting concrete, *ACI Materials Journal*, 98(6): 429-439.

Shao, Y., Lefort, T., Moras, S., & Rodriguez, D. 2000. Studies on concrete containing ground waste glass, *Cement and Concrete Research*, 30(1): 91-100.

Tazawa, E. 1999. Engineering scheme to expedite effective use of resources, In P.K. Metha (ed.), Concrete technology for sustainable development in the twenty-first century, Proc. intern. symp., 23-42. New Delhi, India: Radha Press.

Tittarelli, F. & Moriconi, G. 2002. The effect of fly ash and recycled aggregate on the corrosion resistance of steel in cracked reinforced concrete, In *Durability of building materials and components, Proc. 9th intern. conf., Brisbane, Queensland, Australia, 17-20 March 2002*, Paper 70.

Tittarelli, F. & Moriconi, G. 2005. Re-use of GRP industrial waste in cementitious products, In R.K. Dhir, J.E. Halliday and E. Csetenyi, *Young Researchers' Forum, Proc. 6th intern. congr. on Global Construction: Ultimate Concrete Opportunities, Dundee, Scotland, 5-7 July 2005*, 153-164. London, UK: Thomas Telford.

UNI EN 1052-3: 2003. Methods of test for masonry - Determination of initial shear strength. Ente Nazionale Italiano di Unificazione (UNI) (August 2003).

Zhao, S. 1995. Microstructure and properties of styrene acrylate polymer cement concrete, *Heron*, 40(4): 263-284.