

Sustainable construction materials for concrete: A question of responsible use

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Abstract. This paper has been inspired by the principal author's life-time research at the cutting edge of the concrete industry and is propelled by recent research undertaken with his co-authors, which is referenced fully in this paper. In the main, this work has been created to show that the use of sustainable construction materials, in making concrete, should be carefully evaluated for their rheological, engineering and long-term durability effects, in the relevant exposure classes, as well as environment impacts, in the form of leaching, as a material and whilst in use. Failure to do so, can, in the long-term prove to be disappointingly counterproductive in achieving the estimated sustainability benefits from the use of such materials in concrete, and may even prove disastrous.

Keywords: Sustainable construction materials, environmental impact

1. Introduction

The concrete industry has been growing rapidly, ever since Portland cement was invented, presumably in 1824. The consumption of concrete as a construction material is now second only to water by volume and the statistics for concrete use world-wide are awesome, accounting for about 2 ½ tonnes per person of the global population per annum, with cement consumption reaching close to 5 billion tonnes and with associated aggregate consumption in the region of 30 billion tonnes per annum.

These are huge numbers for natural resources usage, given the associated consumption of energy and pollution of the environment. Thus, it is not surprising that the concrete industry world over has been a major target for lowering CO₂ emissions and promoting sustainable construction, to comply with global sustainability agendas, such as the recently agreed Paris Climate Accord 2015, signed by 195 member states of the United Nations Framework Convention on Climate Change. This agreement aims to keep the global temperature rise this century below 2.0°C, and possibly 1.5°C.

The emphasis on sustainability is bringing about major changes in the construction industry, particularly regarding the promotion of sustainable materials and how concrete is specified and produced, with emphasis rapidly shifting towards the use of waste materials arising from industrial (e.g. fly ash and ground granulated blastfurnace slag (GGBS)) and domestic (e.g. incinerated ash) sectors. In this respect national, regional and international Standards, such as EN 197-1 [1] and EN 12620 [2], which were adopted in Europe at the turn of the century, are classic examples of the



determination of the construction industry to bring about changes in the way cement and aggregates are selected for manufacturing concrete.

Beyond the standards, in efforts to accommodate the use of sustainable construction materials (waste materials), the concrete industry is continually refining the production processes, including an ever-increasing use of chemical admixtures. A shift from prescriptive to performance-based specifications is now part of the evolution that is currently sweeping through the construction industry, albeit slowly at present.

2. Sustainable Construction Materials

The list of sustainable construction materials that can be aimed at the concrete industry has increased noticeably since the turn of this century and this trend is expected to continue as innovation takes hold and pressure grows on the construction industry to further reduce its carbon foot print. It is estimated that at present there is 10 to 20 billion tonnes of waste that can be potentially processed for use.

On the other hand, although the promotion of sustainability is becoming more popular, it must still be recognised that this objective should not grant free reign for any and all use of waste materials in construction. From this perspective, a breakdown of the key aspects of sustainability is presented in Figure 1. Future practices in the construction industry should strive to fulfil each of the social, environmental and economic requirements, to ensure that waste materials are utilised responsibly.



Figure 1: Breakdown of the key aspects of sustainability

The cement industry is already well into the use of first and second generations of Portland-pozzolanic combinations as composite cements, such as those in EN 197-1 [1], namely fly ash, GGBS, pozzolana and burnt shale as bulk replacements of Portland clinker and silica fume in small quantities to refine the pore structure to improve the performance of the cement paste. Pressure to do more in this respect, is encouraging researchers to explore the potential use of a wide-range of the next generation of pozzolanic materials, including incinerated ashes (e.g. sewage sludge ash and municipal incinerated bottom ash), metallic slags (e.g. copper slag) and ceramics (e.g. glass cullet). A comprehensive assessment of these first three as sustainable construction materials is presented in recently published books for each [3, 4 and 5], whilst fourth and fifth books in this series on glass cullet and recycled aggregate are upcoming in 2018. Furthermore, research is also presently ongoing with other researchers to develop CEM-free cements, such as geopolymers in different forms.

In the use of aggregate, the research shows that coarse recycled concrete aggregate (coarse RCA) can replace natural aggregates. Greater emphasis is being placed on refining the production of coarse RCA to further improve its performance in concrete to gain the confidence of engineers. In parallel, other wastes materials such glass, metallic slags, incinerated ashes, quarry fines and marble cuttings

etc. are being developed to further reduce the extraction of natural resources. However, at present, the progress is painfully slow and more concentrated and organised efforts are needed to bring about meaningful fundamental changes.

3. Designing Sustainable Concrete

This is the area where engineering skills, cost-effective and focused R&D and performance-based construction specifications, can all help with the development of mixes that can routinely offer real sustainable concrete, ensuring a long-term durable performance of structures with whole-life costs sustained. This is, in effect, the real challenge facing us all!

3.1. Fresh Concrete Properties

Although often ignored in many ways, the fresh concrete can greatly affect the performance of concrete in the hardened state, including strength development and durability and therefore, the potential sustainability of the resultant product.

Apart from fly ash, GGBS and ground limestone, which have a long history of producing a workable stable mix, free from bleeding and segregation in the fresh state, the suitability of new materials remains to be determined for many. Thus, the performance in the fresh state, with emerging materials replacing the currently used constituents, in the form of cement and/or aggregate as coarse, fine or filler, can often be a critical factor in deciding their acceptance for use. The specifications for the performance of fresh concrete must not be ignored in developing the use of new materials, as in some cases, these may limit their use. For example, with sewage sludge ash (SSA) and municipal incinerated bottom ash (MIBA), extra water demands arising from their morphology and high porosity [6] would have to be accounted for when using the ashes as aggregate and in ground form, as a cement component in concrete [7-9].

3.2. Strength

Whilst, in principle, applying Abrams law relating strength to water/cement ratio, a concrete mix can be designed with any set of materials by adjusting the water/cement ratio, and thereby the cement content, to comply with a given specified strength; however, an increased cement content may negate the potential environmental benefits of using materials sourced as recycled, industrial by-products, or incinerated domestic waste, Figure 2 [10]. This would often require coming up with a solution, which may include the use of a water-reducing admixture, to make it feasible to use the new materials, whilst retaining potential environment benefits. In a commercial sense, the material variability, together with increased rate of testing for quality control would also have to be considered in assessing the viability of the new materials in practice. However, this may not rule out the use of new materials with low grade concrete mixes, which could still offer some environmental benefits.

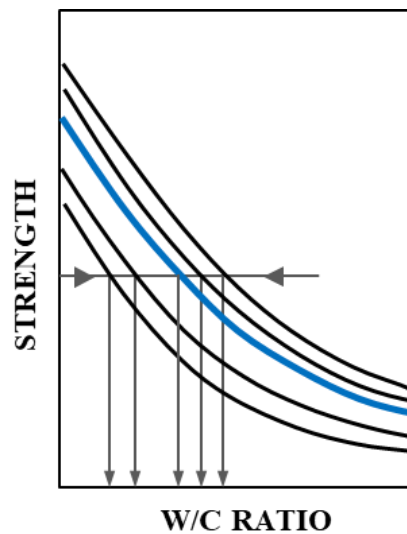


Figure 2: Relationship between strength and water/cement ratio

In assessing the potential use of constituent materials, a pragmatic approach to their sustainable application can greatly widen the scope for the new materials to be adopted in concrete construction, as illustrated in Figure 3 [11].

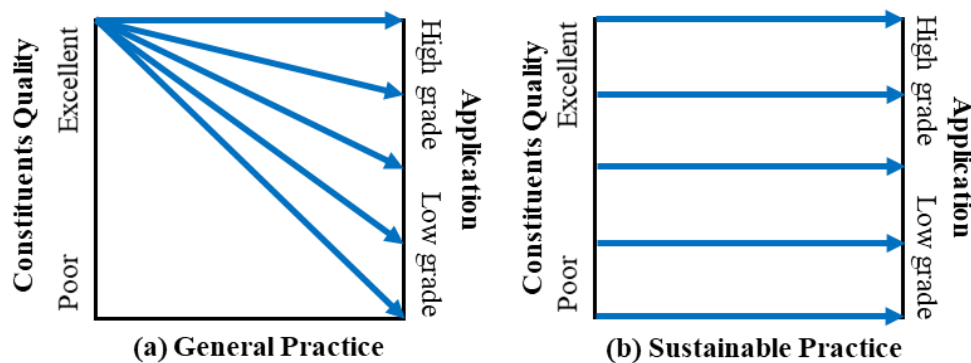


Figure 3: (a) General practice and (b) sustainable practice in dealing with constituent materials

3.3. Deformation Properties

Structural concrete also has to be designed for its elastic, creep and shrinkage deformation properties (Eurocode 2) [12] (though in practice these parameters are largely estimated from its compressive strength). Figure 4 has been prepared to show the outcome of an analysis of a large volume globally sourced data matrix (50,000 data points) based on the research undertaken since 1977 by 860 researchers at 537 institutions in 46 countries, to assess the effect of using coarse RCA, and glass cullet and copper slag as fine aggregates (fine GCA and CSA) on the modulus of elasticity, creep and shrinkage [13-17].

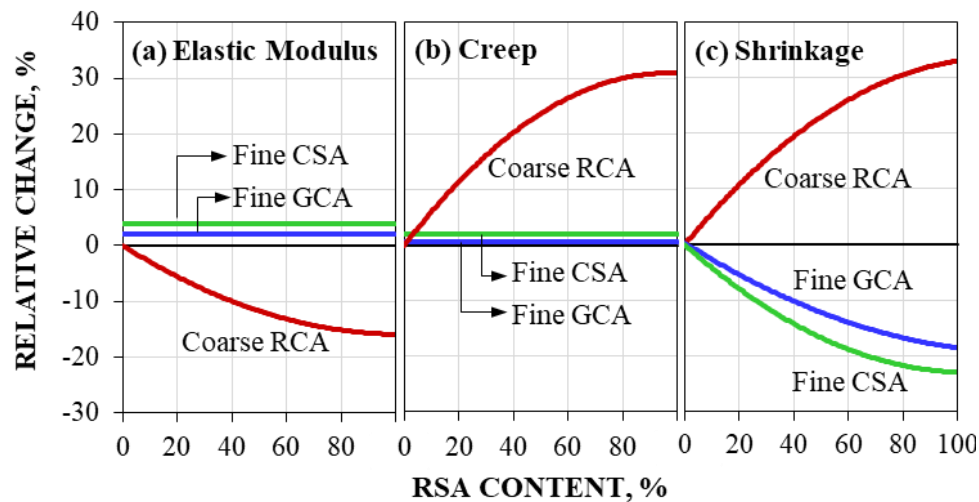


Figure 4: (a) Elastic modulus, (b) creep and (c) shrinkage of recycled and secondary aggregate (RSA) concrete

These studies concluded that, whilst fine GCA and fine CSA can replace fine natural aggregate (NA), the use of coarse RCA in place of coarse NA in structural concrete, in its current form, will adversely affect the deformation properties. These studies also suggested that whilst the use of fly ash and a water-reducing admixture alongside the coarse RCA, to a certain extent closed the gap towards obtaining the required deformation properties, additional material costs would have to be sustained.

The use of a blended aggregate, in this case, coarse RCA mixed with fine CSA, may allow sustainability benefits to be retained, as the fine CS would improve the consistence (workability) and thereby allow the mix water content to be reduced, without having to use a water-reducing admixture [13]. However, further study would be required to formulate how best certain materials, such as CS, with low water demand, can as fine aggregate, be blended with coarse RCA to minimise its negative impact on the deformation properties of concrete. This would be a challenging research project.

3.4. Durability

For sustainable materials to be considered suitable for use as an aggregate and/or cement in manufacturing concrete, the durability performance, in all aspects relating to the application, should not be adversely affected. Taking the case of a pozzolanic material used as a component of Portland clinker-based blended cement, for the pozzolanic to perform, some of the alkalinity released from the Portland cement hydration will be taken up to activate the pozzolanic reaction to form calcium silicate hydrates (the cementitious products).

In a CO₂-environment, the use of a Portland-pozzolanic blended cement would lower the pH of the concrete, unless compensated with moist curing forming a densified cement paste pore structure, which helps to reduce the permeation properties, and in turn, control the alkalinity of the concrete.

To assess the carbonation effect of fly ash, GGBS and limestone, a global data-matrix with 79000 entries, built from 583 studies, published since 1968, and undertaken by 983 researchers from 494 institutions in 41 countries were analysed [18-20]. The trend lines obtained are shown in Figure 5.

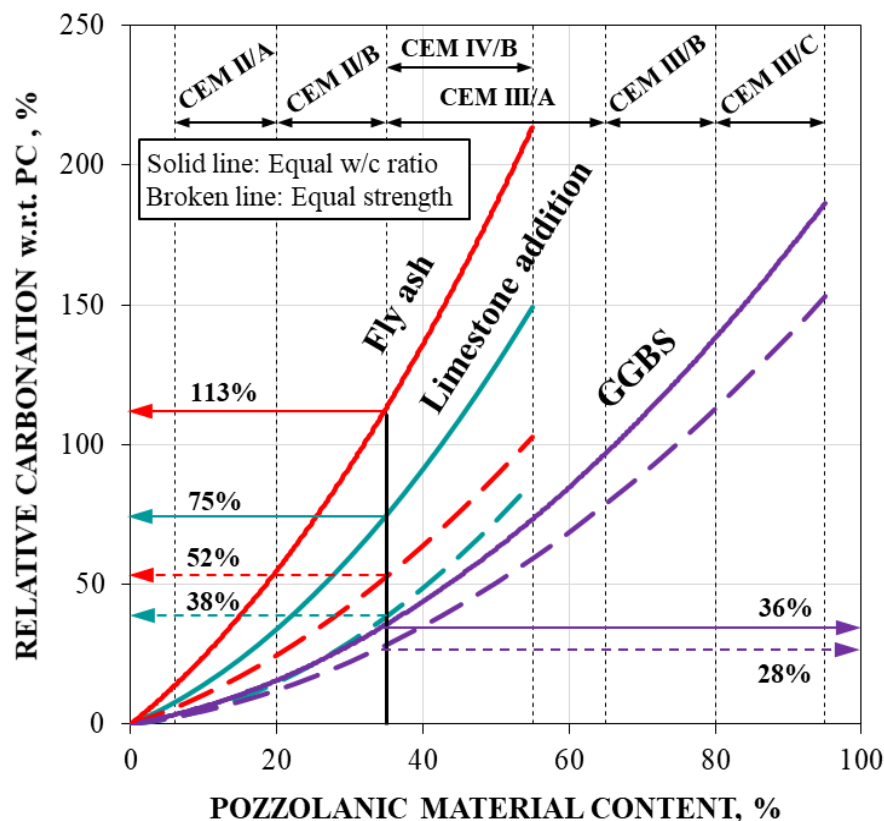


Figure 5: Effect of pozzolanic materials on the carbonation of concrete

This shows that concrete designed using EN 197-1 [1] Portland-based, fly ash, GGBS and limestone cements can be expected to show higher rates of carbonation than the corresponding Portland cement (PC) concrete. The increase in carbonation depth varies with the addition type, with fly ash giving the highest increase. For example, reading from Figure 5, with an equal water cement ratio and 35% fly ash addition, the concrete exhibited a 113% increase in carbonation compared to PC mix. Corresponding increases of 75% for limestone and 36% for GGBS were also determined. However, when the concrete is specified for a given strength, for the same 35% addition, the corresponding carbonation increases drop to 52% for fly ash, 38% for limestone and 28% for GGBS.

This increase in the depth of carbonation presents a risk of early carbonation-induced corrosion and reduces the concrete durability, which in turn adversely affects the sustainability impact gained from using these materials. As all pozzolanic cementitious materials consume Ca(OH)_2 , released upon hydration of Portland cement, their use as Portland-Pozzolanic cement combinations could potentially present a serious durability risk. It has also been established that combined effects of carbonation and chloride ingress further increase the susceptibility of the concrete to corrosion [21].

Focusing on the use of limestone, a comparison of its overall effects, relative to PC concrete, on the pore structure, durability and strength is presented in Figure 6. Simple modifications have been carried out to the trend lines in this figure, changing from previously developed polynomial regression curves [20, 22, 23] to linear regression, as in this case, the goal was to produce a useful tool that could be more easily adopted in practice. For practical purposes, it is feasible to accept that for limestone contents up to 15%, the effects may be considered constant and close to neutral. Increasing limestone beyond 15% gives rise to a progressive reduction of the concrete properties, in this case, the pore structure, durability and strength. As such, it is concluded that limestone can be incorporated at

contents up to 15% without significantly comprising the concrete performance, which is below the maximum 20% limit for CEM II/A for Portland limestone cement in EN 197-1 [1].

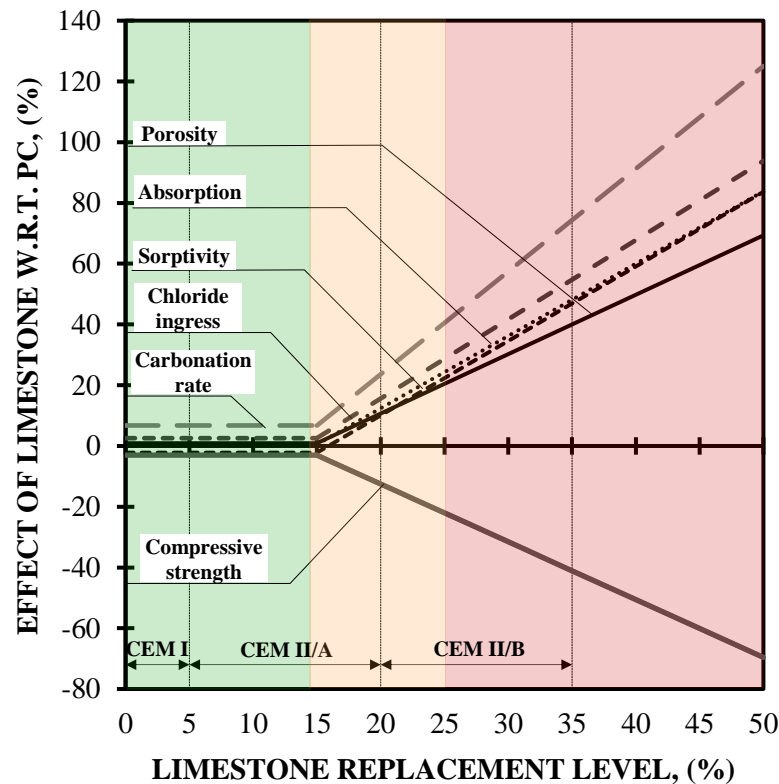


Figure 6: Limestone effects on pore structure and related properties, compressive strength, carbonation rate and chloride ingress of concrete [23].

Regarding the use of municipal incinerated bottom ash as aggregate in concrete, a ranking of the effects on various aspects of durability is presented in Figure 7 [8]. On the permeation properties, measured as absorption and initial surface absorption, decreasing durability was evident with MIBA. For aggregate replacement levels greater than 25%, initial surface absorption of the concrete drifted above the 0.5 ml/m²/s upper limit for normal-strength concrete. This suggests that the ash contents may have to be controlled to lower levels. Increases in the chloride diffusion coefficient occurred with MIBA, owing to the higher overall mix porosity. The effect on sulphate attack susceptibility was classed as neutral, as concrete containing 25%–100% MIBA as fine or coarse aggregate exhibited no extra expansion.

Carbonation resistance improved slightly with MIBA (reduced carbonation depths). As carbonation is sensitive to moisture conditions, the extra water absorbed by MIBA appeared to be beneficial in slowing down the carbonation ingress, despite higher permeation. MIBA mixes displayed comparable or superior freeze/thaw resistance compared to the control, as the higher porosity of the aggregates can act as an air-entrainer. Alkali-silica expansion potential of MIBA concrete exceeded that of the natural aggregate mix; however, the validity of this outcome appears questionable, as the control limestone blend also greatly exceeded the limit that signifies potential alkali-silica reactivity. Indeed, a second test series, involving both laboratory and field work, revealed no evidence of silicate gel expansion.

	Negative Effect	Neutral Effect	Positive Effect	
MIBA as 50% fine agg	■			Permeation
MIBA as 50% fine agg	■			
MIBA as 50% coarse agg	■			
MIBA as 20% coarse agg	■			Chloride Corrosion
MIBA as 20% fine+coarse agg	■			
MIBA as 25-100% fine agg		■		Sulphate Attack
MIBA as 25-100% coarse agg		■		
MIBA as 20% coarse agg			■	Carbonation
MIBA as 20% fine+coarse agg			■	
MIBA as 20% coarse agg			■	Freeze/Thaw & Frost Resistance
MIBA as 20% fine+coarse agg			■	
MIBA as 10% fine agg		■		
MIBA as 100% coarse agg		■		
MIBA as 100% coarse agg	■			Alkali Silica Attack
MIBA as 100% coarse agg	■	■		

Figure 7: Effects of MIBA as aggregate on concrete durability

3.5. Environmental Impacts

Use of sustainable construction materials must be predicated on ensuring that there are no detrimental impacts on the surrounding environment, arising from leaching. With a notable presence of heavy metals in MIBA and SSA, tests have been undertaken to assess their leaching in use.

However, as traditional construction materials generally do not contain harmful amounts of metals, most standards do not account for these issues. Countries such as Germany, Denmark and The Netherlands have developed guidelines for leaching limits for waste materials reuse, though with MIBA and SSA use in construction products, there was a large variety of leaching test methods adopted and heavy metal limits applied. The emerging consensus was that the restriction of the ash-products' leaching to suitable levels requires certain conditions to be adopted regarding the pre-processing of the ash (e.g. ageing and washing treatments) and limitations to avoid unfavourable leaching conditions such as strongly acidic conditions or high rainfall regions [24 and 25].

Covering the various applications in which incinerated ash has been explored, an estimated ranking of the leaching potential in each is presented in Figure 8. The potential is highest in the ground as fill or subbase, as the ash is unbound and there is a direct pathway for the metals to travel into sensitive receptors such as water sources. In lightweight aggregate production, the heat treatment and hard outer layer formed is somewhat beneficial in restricting the mobility of the heavy metals, though with the extra inclusion of a binder fraction (cement or clay) in the aggregate blend, the leaching reduces greatly. In mortar and concrete mixes, as well as hydraulically bound pavements, the cement provides solidification (physical encapsulation) and stabilisation (chemical binding) effects, though there are some questions regarding leaching after the product's deterioration or demolition and increased solubility of some elements in alkaline conditions. The hydrophobic nature and binding ability of bitumen translated into low leaching potential in these pavement mixtures. Low heavy metal leaching was measured for tiles and glass ceramics, owing to the restricting effect of clay and the very high

temperatures involves in the production process. Combined positive effects of the heat treatment, cement binding and low ash contents adopted in cement clinker production also led to low leaching.



Figure 8: In-use leaching of incinerated ash

4. Cost Considerations

As economic viability is a key pillar of sustainability, a realistic audit of any sustainable material use (in the form of reuse, recycle or reconstitution) in concrete construction should to begin with, be made on an equal strength basis, allowing for factors relating to variability in product performance. There are already some suggestions for moving the specification of concrete characteristic strength from 28 days to 56 days, to promote the use of certain pozzolanic materials, such as coal fly ash and GGBS. It is not certain whether this change would help the suitability of other pozzolanic materials for use in bulk, such as rice husk ash.

The role of other engineering properties in designing structures, such as the load related and load independent deformation, is critical and cannot be ignored. Indeed, it can be argued that given the results presented in Figure 4, the proportion of some sustainable materials that can be used, in their present form, is likely to be limited e.g. in the case of recycled concrete aggregate it may be about 20%, beyond which additional costs will be incurred.

Additionally, all aspects of increased costs arising from changes in durability should be taken into consideration, for example, a potential reduction in the resistance of the reinforcement to corrosion, as illustrated in Figures 5-7. In this case it would be fair to say that the sustainable materials have not been subjected to the rigour of a systematic evaluation, though a large number of studies have been undertaken and an even larger volume of publications have been produced.

Finally, there are issues of environment impact that need to be addressed, where there is a lack of harmonisation in the evaluation processes and the information available is rather sparse, not commonly understood and often does not inspire confidence. Indeed, it is a difficult field to explore and it could be argued that perhaps the construction industry at present is not well prepared to handle such environment issues.

5. Balanced Approach

A balanced approach, based on a realistic assessment, as opposed to short-term commercial gain is needed in developing the use of sustainable construction materials, both as cement and aggregate components in concrete. This is important, as failure to do so can prove to be extremely expensive and do little to promote the use of sustainable materials in construction.

6. Conclusions

- The concrete sector has a significant role to play in the development of sustainable construction.
- Whilst the use of sustainable construction materials is potentially an attractive proposition, to minimise any long-term risk to durability with concrete construction, their use should be carefully evaluated and must not be based on strength only. In this respect, deformation properties should also be evaluated.
- The use of all pozzolanic materials and recycled materials with high porosity in structural concrete, in certain exposure classes, carry risks in the pursuit of sustainable construction.
- When using secondary materials that contain heavy metals and pose a potential leaching risk, the environmental aspect of sustainability must be carefully assessed.
- Clearly whilst further research is badly needed, given that the stakes can be high, it must be ethical, robust and thorough using standards which are well explained and understood.
- This research should also be:
 - (i) Reproducible, dependable and inspire confidence through international collaboration for universal endorsement.
 - (ii) Leaning on industrial involvement, though it is considered to be an essential requirement.
 - (iii) Innovative, imaginative, progressive, bold and deliverable.
 - (iv) Conclusive, explaining clearly the methodologies and test procedures adopted, and yield recommendations that are doable, clear and of practical relevance.

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