

A PRELIMINARY EVALUATION OF THE REUSE OF CEMENTITIOUS MATERIALS

P PAIGE-GREEN

CSIR Built Environment, P O Box 395, Pretoria, 0001
(e-mail: Ppaigeqr@csir.co.za)

ABSTRACT

The recycling of existing stabilized road pavement layers is becoming increasingly common as the South African road network ages and is being continually rehabilitated. In addition, large quantities of old concrete road, building rubble and demolition waste are being generated on an ongoing basis. Many of these materials still contain significant proportions of cementitious components that can be used to improve the quality of the materials being recycled, but can also lead to problems with over-stabilization of certain materials. A preliminary study into the self-cementation of various recyclable materials has been carried out and the results are reported in relation to their potential for wider use in South Africa. The scope for wider reuse of these materials is discussed.

1 INTRODUCTION

In the interests of economy, expedience of construction and sustainability, there is an increasing need to reuse existing construction materials during rehabilitation of old roads. Other than the limited use of recycled asphalt (RA) and the increasing use of existing pavement materials (usually through in situ recycling), little use has been made of many of the waste materials available in South Africa for road construction and little technical information is available for many of them. The use of recycled materials certainly has environmental benefits, both by minimising extraction of virgin materials and by reducing the quantity of waste removed to landfills.

Recent research at the CSIR has shown that many of these materials can still have some residual binder (cement or possibly lime), which could be either beneficial or detrimental, depending on the use of the recycled material. It is suspected that the residual binder can continue to react in the recycled material producing some "self cementation" effect. However, there is still a lack of knowledge and experience regarding the stabilization of previously stabilized materials, whether they had been stabilized some time previously or are in materials that have been rejected during current construction (failing the standard quality requirements) and require reworking.

This paper discusses the results of an investigation of the literature and some laboratory testing that has been carried out. It should be noted that this paper primarily addresses the reuse of materials that have been previously treated with conventional stabilizers (ie, lime or cement) to assess the likelihood of the material re-cementing on the basis of residual stabilizer. Materials initially stabilized with other stabilizers such as bitumen and proprietary soil stabilizers were not included in this study and are unlikely to have similar beneficial (or detrimental if not understood) effects on recycling.

2 POTENTIAL MATERIALS FOR RECYCLING

Apart from the obvious substitution of natural resources with conventional industrial waste materials, many other materials currently disposed of in landfills and dumps could be profitably used in road construction. These materials include construction and demolition waste including concrete (C&DW) and previously stabilized road materials. All of these materials potentially contain residual cementitious material and could be recycled.

The literature (Yeo and Sharp, 1997; Aggregate and Quarry Association of New Zealand, 2001) and an internet search shows that most of the previous work has been on recycled/reclaimed concrete and Australia seems to be the current leader in the field. A number of references to potential recycling of concrete in roads were located on the internet but no specific references could be found to recycling of previously stabilized road materials or the influence of any residual cementitious stabilizer. Significant reference is, however, made to the use of recycled construction and demolition waste (C&DW) in roads, mostly by commercial enterprises marketing the equipment for processing the materials and those actually marketing the processed materials. Very few of the references contained test results or discussion of the properties of recycled materials that had not been re-stabilized: the addition of new stabilizer appears to be the norm in recycling.

Although recycled concrete is likely to have a higher proportion of residual cementitious material in it than typical demolition rubble, the resulting crushed materials are essentially similar, depending on the sorting and crushing techniques used.

In one of the few references to actual re-cementation (Yeo and Sharp, 1997), it has been shown that recycled crushed concrete without the addition of extra stabilizer increased in strength by about 50 % between 7 and 28 days and by 125 % after 90 days. Under accelerated curing an increase in 109 % occurred between 7 and 28 days. All of these materials had strengths between 2.2 and 2.7 MPa after curing, well within that specified for typical well cemented materials in South Africa (COLTO, 1998). What was of particular interest was that the host material gained strength at a similar rate to the material when additional stabilizer was added (Yeo and Sharp, 1997).

Although no test results are provided in the document, proposed guidelines for the use of recycled concrete products in New Zealand (Aggregate and Quarry Association of New Zealand, 2001) specify a maximum unconfined compressive strength for the use of recycled concrete in pavement layers of 3.5 MPa. This test is done without the addition of stabilizer and the limit is included to ensure that the residual cementitious binder in the crushed products does not cause the pavement to act as a semi-rigid structure and hence suffer possible fatigue cracking.

The effect of residual binder as a stabilizer has also been reported from Minnesota and California (FHWA, 2004). This additional benefit has resulted in recycled concrete becoming the base aggregate of choice in these two states.

Besides these important findings from the USA and Australia, very little work on the re-cementation properties of recycled concrete has been carried out. Nothing specifically on recycled stabilized road materials seems to have been reported at all.

An important but not directly related aspect regarding recycling is that any previously stabilized material containing residual lime, cement or cementitious products will act as a

carbon dioxide sink, absorbing carbon dioxide from the atmosphere. This can have important sustainability implications in the overall recycling-disposal scenario.

3 PROBLEMS

A number of problems related to recycling of materials have been encountered, but with care these can be managed. These include high material variability and the inclusion of detrimental particles (Poggiolini, 2007) but the most significant aspect related to their use and the issue that this paper concentrates on is the possible generation of excessive strength derived from hydration of the residual binders.

The problems related to excessive stabilization normally manifest as excessive stabilization (or block) cracking or a pavement layer that is so stiff that it becomes excessively brittle in terms of the total pavement structure, and is subject to early fatigue failure if the pavement structure is not designed to cater for this. These can result from the unexpected “self-stabilization” of the materials when additional stabilizer is added, without being aware that the material already has a stabilization potential.

This is related in many respects to the problem of reworking of stabilized layers that have been constructed and rejected when they do not comply with the specification requirements of the project. It is normal to add half of the original stabilizer again (Gautrans, 2004) when reworking and if still unsuccessful, the material should be removed and spoiled. There are still many unknowns regarding the re-stabilization and reworking of such materials to avoid excessive stabilization cracking, but the potential problem has been recognised and is usually taken into consideration during projects. The addition of stabilizer to any material more than twice is generally not allowed and it then becomes necessary to spoil the material with severe cost and environmental implications.

4 BACKGROUND TO INVESTIGATION

This investigation started as the result of the investigation of a road that was originally built in 1969 with a C1 cement stabilized base. This developed extreme cracking and had to be rebuilt in 1974 with extraordinary performance. The material that was used for the original construction of the highly cemented base course was reworked with the addition of a nominal quantity of bitumen emulsion (17 l/m^3 or 0.5% residual bitumen). By 2004, significant strengths (soaked unconfined compressive strengths (UCS) of 3.1 to 5.5 MPa) had developed in the layer (Table 1). Even after full accelerated laboratory carbonation (modified after De Wet and Taute, 1985), the materials had unexpectedly high compressive strengths. Materials that had been stored for nearly two years had carbonated unconfined compressive strengths between 2.3 and 4.3 MPa, while freshly cored materials had residual strengths after carbonation of about 4.5 MPa (Table 1). Both the high natural strengths and the fact that these decreased on carbonation led to the preliminary, but somewhat contentious, conclusion that the high strength was probably due more to secondary pozzolanic stabilization than any strength developed by the bitumen emulsion. Re-cementation of the material by the hydration of residual stabilizer was thus proposed as the cause of these high strengths, but this was not accepted by a number of practitioners.

Table 1: Results of UCS testing before and after accelerated carbonation

Sample	Treatment	UCS (MPa)	Phenolphthalein Reaction
2 year old cores	Untreated	3.1 – 5.5	Strong
	Carbonated	2.3 – 4.3	None
Freshly drilled cores	Untreated	4.7 – 5.5	Strong
	Carbonated	4.4 – 4.8	None

It was, however, difficult to determine whether the bitumen played a significant role in the strength development. After some deliberation, an experiment was devised to check whether heating of the sample would soften the bitumen and have an effect on the material strength. This would need to be done without any drying of the sample in order to minimise carbonation and testing at different moisture contents. The samples were thus heated to 25°C, 50°C and 75°C in sealed packing after correcting the ends with Plaster of Paris to ensure parallel and even seating. They were then subjected (in duplicate) to conventional unconfined compressive strength testing (unsoaked) at the raised temperatures. Two batches of samples were treated in this way – one (batch 1) after being stored in sealed plastic bags for about 2 years after coring and the second (batch 2) within two weeks of coring.

The results obtained are summarised in Table 2.

Table 2: Results of UCS testing at different temperatures

Temperature (°C)	Strength (MPa) Batch 1	% change	Strength (MPa) Batch 2	% change
25	5.4	0	5.0	0
50	4.3	-21	4.9	-1,8
75	4.0	-26	4.7	-6,1

If it is assumed that heating of the materials resulted in softening of the bitumen only (probably a reasonable assumption bearing in mind the heating conditions), the progressive decrease in strength on heating is indicative of some bonding produced by the bitumen. Direct carbonation of the specimens resulted in a decrease in strength of between 12 and 28% (based on the data in Table 1). On this basis it was concluded that the contribution of the bitumen binder to the strength of the material was probably similar to that of the re-cementation, a rather surprising fact based on the very small quantity of bitumen emulsion added during the reconstruction. The smaller decrease in strength of the Batch 2 samples (essentially non-carbonated) on heating, however, indicates that the contribution of the bitumen to the strength of non-carbonated materials is considerably smaller.

After UCS testing of the cores, specimens were taken for examination using a Scanning Electron Microscope (SEM). Six different specimens were studied and it was concluded that:

- The matrix of the recycled base had residual cement (or possibly lime) from the recycled cement stabilized layer that was able to hydrate and form second generation cementitious bonds (Figures 1 and 2).
- The presence of potential stabilization products (including $\text{Ca}(\text{OH})_2$) was confirmed by the presence of calcium carbonate (CaCO_3) formed during carbonation (Figures 3 and 4)
- The overwhelming presence of cementitious reaction products compared with the bitumen presence and the almost ubiquitous presence of well-crystallized calcite (which indicates recent formation of this material) lead to the following conclusions.
- The dominant mode of stabilization was through cementitious bonds between the aggregate/particles and the reaction products of lime and/or cement released during breaking up of the previously highly stabilized base.

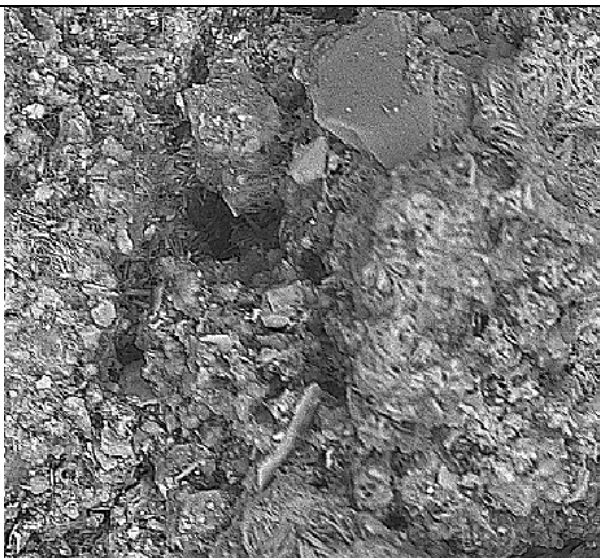


Figure 1: “New” cementation crystals adjacent to and growing into voids (x 940)

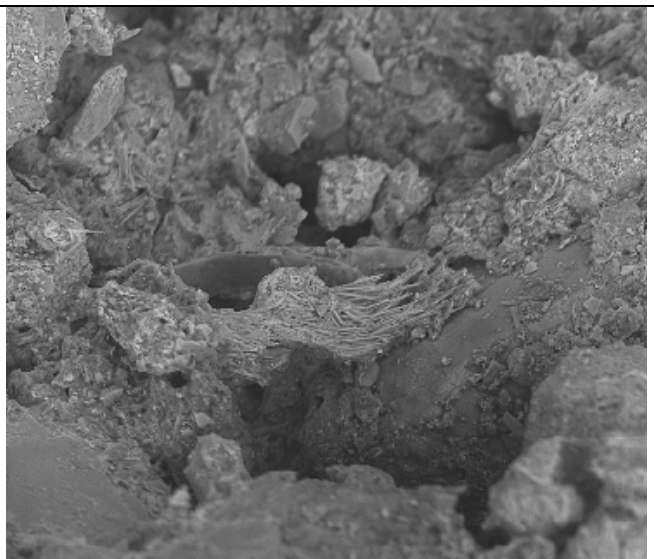


Figure 2: Second generation crystals of cement reaction products and wispy ettringite crystals (x 200)

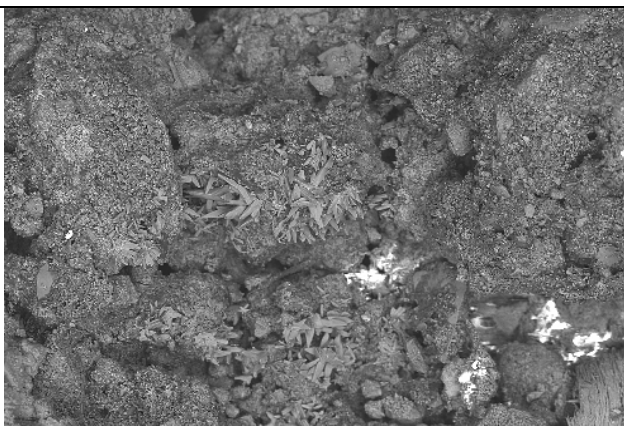


Figure 3: Development of young calcite crystals associated with cracks (x70)

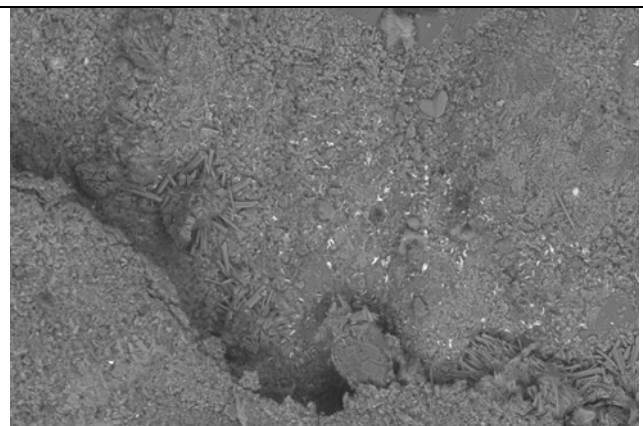


Figure 4: Development of calcite crystals associated with cracking during carbonation (x180)

5 LABORATORY RE-CEMENTATION INVESTIGATION

Based on the work discussed, it became clear that re-cementation of certain previously cemented materials was likely to be a viable process. Thus, in order to assess the typical re-cementation properties of a range of materials, various concrete and stabilized materials were collected from construction sites or other potential sources of cementitious materials covering as wide a range of ages as possible. In all, 15 bulk samples with their origin and estimated ages indicated, were collected from various locations for testing (Table 3).

Table 3: Number, nature and estimated ages of samples obtained

Sample	Material type	Estimated age (yrs)
1	Concrete from highway	30
2	Stabilized base course	30
3	Waste builders rubble	Variable
4	Waste builders rubble	Variable
5	Waste builders rubble	Variable
6	Waste builders rubble	Variable
7	Concrete pedestal	53
8	Old CBR soaking bath	53
9	Wing-wall from bridge being upgraded	30
10	Cast in situ concrete driveway	25
11	Foundation beneath tiled patio	13
12	Wing-wall of demolished bridge	30
13	Stabilized base course	31
14	Stabilized base course	31
15*	Concrete from highway	32

* - Sample 15 was the same as Sample 1, but was heavily ground to increase the fines content

The grading, plasticity, compaction characteristics and pH of each of the materials were determined. The samples were then compacted into conventional CBR moulds at optimum moisture content to 100% Mod AASHTO density (TMH 1, 1987) and allowed to cure for 7 (some samples), 28 and 56 days. The specimens were removed from their compaction moulds after 7 days curing, at which point the majority of them had developed sufficient strength to allow handling without disintegrating. In some cases two batches of duplicate samples were compacted, with one batch being cured in a humidity room and the other placed on a laboratory shelf at 25°C and 50% relative humidity. All samples were tested in duplicate for the UCS after soaking for 4 hours.

The results of the testing are summarised in Table 4.

Table 4: Results of UCS testing

Sample Number	Treatment	Unconfined Compressive strength (MPa) after days		
		7	28	56
1	Laboratory shelf	1.7	3.3	2.2
	Humid room	1.6	1.8	2.4
2	Laboratory shelf	-	1.2	1.1
	Humid room	-	3.0	2.8
3	Humid room	1.7	1.6	1.5
4	Humid room	1.8	2.3	2.8
5	Humid room	1.6	2.2	2.2
6	Humid room	1.5	1.4	1.4
7	Humid room	-	1.1	2.7
8	Humid room	-	2.1	2.6
9	Humid room	-	0.8	2.4
10	Humid room	-	1.8	2.6
11	Humid room	-	1.1	2.9
12	Humid room	-	1.5	2.1
13	Laboratory shelf	1.0	1.2	0.7
	Humid room	0.3	0.3	0.2
14	Laboratory shelf	1.0	0.9	1.1
	Humid room	0.3	0.4	0.7
15	Laboratory shelf	3.7	2.8	2.7
	Humid room	3.5	3.4	3.2

6 DISCUSSION

It is clear that under humid curing conditions, in many cases there is an increase in strength between 28 and 56 days indicating that continuing cementation occurs as a result of the residual binder (Figure 5). Three of the materials showed slightly lower strengths at 56 days compared with the 28 day strengths but all of these had 28 day strengths in excess of 1.5 MPa (ie, C3 equivalent) and the differences were small (probably within the repeatability of the preparation and test techniques).

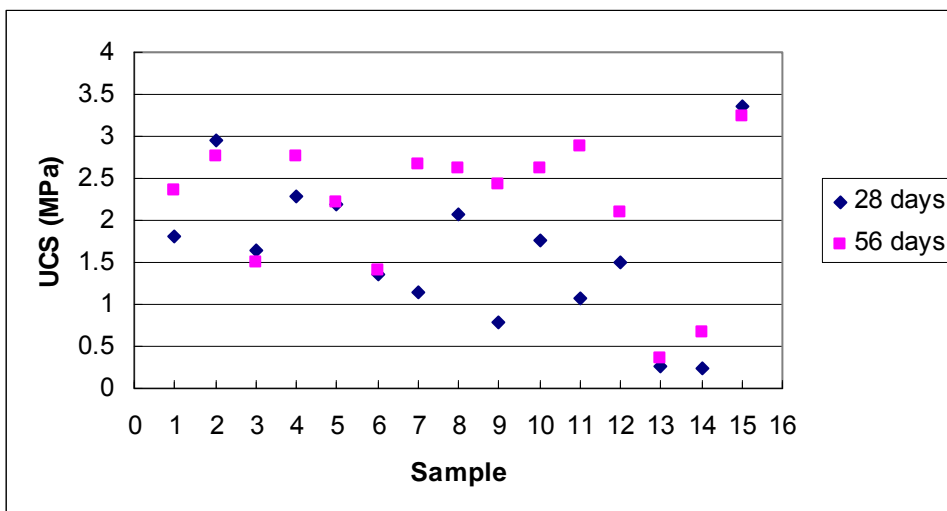


Figure 5: Plot of UCS versus pH of material after 28 and 56 days

Mixed results were obtained on the few materials that were allowed to cure exposed to air in the laboratory. Half of the specimens gave higher strengths than the normally cured materials up to 28 days, mostly with decreases thereafter. This is probably indicative of a lack of moisture in the specimens to allow complete/continued hydration of the cementitious products.

Figure 6 was plotted to examine the hypothesis that the degree of re-cementation is related to the initial pH of the material. A pH in excess of 9 indicates the presence of some residual stabilizer. Although there are little data between a pH of 9.5 and 10.5, the results show a strong trend that if the pH is above about 9.5, significant self-cementation will occur, generally producing strengths between 1.5 and 3.4 MPa (equivalent to up to C2 materials) after 56 days. It is thus also possible that if these materials are reworked with additional stabilizer, unacceptable stabilization cracking could arise.

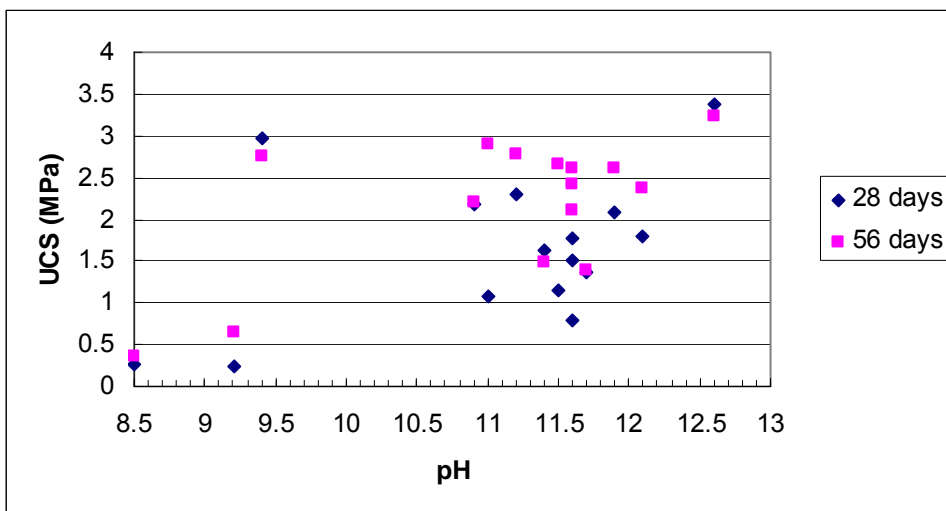


Figure 6: Plot of 28 and 56 day UCS for the various materials

Bearing in mind the small percentage of fines generated by the laboratory crushing and that the predominant content of residual cementing agent would be in these fines, the increase in strength is significant. Better crushing procedures with the generation of a greater percentage of fines (up to 12% fine is usually required in crushed stone) would probably result in much higher strengths. The less and the smaller the voids in the compacted material (a function of the quantity of fines) the higher the cemented strength is likely to be, as the growth of cementation products within these voids would bridge between the particles better and fill the voids in finer materials. The production of finer materials would often be achieved in the field by using milling or recycling machines and adjusting settings and speeds, but could prove difficult on strong concrete.

Sample 15 is the same as Sample 1 after additional crushing to generate more fines. The other samples were typically obtained in a relatively granular form and were tested without additional processing (other than scalping at 19 mm).

It is important in this type of work to try and isolate samples from the air prior to the laboratory work. Those materials with a low pH (< 10) can carbonate rapidly when handled and processed in the laboratory, particularly when testing the pH, leading to non-representative results. Similarly, low pH materials when stored in unsealed (or torn) bags for too long prior to testing can lose much of their re-cementation potential as a result of carbonation. Testing should thus be carried out as soon as possible after sampling.

Construction and Demolition Wastes are increasingly being considered as carbon dioxide sinks, as any remaining lime or cement will continue to absorb carbon dioxide from the atmosphere until their pH is less than about 8.8.

The Scanning Electron Microscope investigation has provided definite evidence of re-cementation, and additional work using this tool has been planned on the materials currently being investigated in the laboratory. The reduction in strength of previously cemented materials treated with bitumen brought about by heating the samples indicate that binding by the bitumen has a limited but positive effect on the strength of the material, but that developed by the secondary cementation is probably the principal contribution. It should be noted that road surface temperatures as high as 70°C are not uncommon, and reliance on the strength contribution of the bitumen emulsion could result in problems in the upper parts of bitumen treated layers in hot areas.

It is clear that the use of recycled materials with residual stabilizer requires certain production and storage techniques as well as special specification and usage practices. However, the benefits from all aspects are substantial, although the potential for excessive stabilization and the potential problems associated with this should always be considered.

7 CONCLUSIONS

The recycling of construction and demolition waste will in future be driven by reduced landfill availability, government recycling mandates, environmental concerns, increasing cost of natural materials, greater product acceptance and the continuing decay of older infrastructure. These materials may or may not contain residual cementitious binder, depending on their ages, the environment in which they performed, the original mix designs and various other intrinsic properties.

An analysis of the literature shows that although many instances of the use of recycled concrete and demolition waste are referenced, there is very little hard data regarding the properties and behaviour of the materials. The majority of the references refer to the philosophical and environmental benefits of reusing these materials that are currently primarily deposited in landfills. Limited work in Australia and the United States has conclusively shown that re-cementation in recycled concrete is a real phenomenon and can be used beneficially in roads. However, no specific tests to give early indications of potential re-cementation have been developed as yet.

Despite the scepticism of a number of local practitioners regarding the potential for re-cementation of recycled stabilized materials, the potential for this has been shown to be high. There is no doubt that most recycled concrete has a significant residual binder content, and previously stabilized pavement materials certainly have some residual stabilizer. Rapid techniques for the quantification of the potential of recycled materials to re-cement need to be developed.

Surprisingly, little research has been directed towards the optimum classification and use of this residual binder, considering the potential benefits that can be derived from it, as well as possible problems associated with severe cracking if additional stabilizer is added.

8 ACKNOWLEDGEMENTS

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