SAND QUALITY CONTRIBUTION IN PRODUCING LOW CARBON CONCRETE

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SUMMARY

Significant advances are being made developing concrete mixes with lower embodied carbon by using supplementary cementitious materials, chemical admixtures and special additives. While these initiatives have the potential to make a step change in carbon emissions of concrete in New Zealand, there are still simple savings possible by better optimisation of materials. The quality of fine aggregates has been under pressure recently as quarries struggled to supply record volumes to readymix concrete suppliers. This paper considers how the quality of concrete sand can influence the cementitious content of concrete.

Sand quality is often inferred from basic grading analysis such that fineness modulus becomes the main form of quality assessment of the material. While fine modulus is a useful production control measure, it was never intended to provide a full assessment of sand quality. Traditionally, concrete technology considers the contribution of particle shape and texture since these also have a significant effect of fresh and hardened properties of concrete but are rarely tested by quarries or in production laboratories. An experimental review was undertaken across a range of natural and manufactured sands using established and newer techniques. Sand quality was assessed using the NZ sand flow test and modern techniques including slurry testing and digital image analysis, with these results compared with the performance of concrete mixes made using these sand types.

Cement contents for any structural grade of concrete can vary by as much as 30% across production locations in New Zealand. Whilst there are several contributing factors to this variation in cement content, this research shows that aggregate shape and texture plays a significant role especially with regard to concrete sands. Poor shape control of fine aggregate leads to higher water demand and this is often associated with higher cementitious contents in concrete. Recommendations are made in this paper that would allow easy assessment of sand quality especially when blending natural and manufactured sands is undertaken by quarries. Conclusions also show that significant cement savings and therefore carbon emissions can be made by investing in better control of the quality of fine aggregate.

INTRODUCTION

Reduction of embodied carbon in concrete has focused on using supplementary cementitious materials to replace Portland cement. While most embodied carbon in concrete is from cementitious sources (e.g. typically 85-90%), there has been less attention paid to the role of aggregate to this issue (Alexander et al 2019). Pressure has also increased on aggregate supply that sometimes has negatively affect the quality of aggregates and in consequence this may increase the amount of cementitious material. These variations in concrete mixes are often related to the quality of sand used in concrete that contributes to cement contents ranging by as much as 30% within New Zealand.

Traditionally, the quality of fine aggregate has been assessed primarily from the particle size distribution or grading and even this has been reduced to relying on a single metric, the fineness modulus (FM) of a sand. Particle shape has either been ignored or assumed to not change significantly especially when natural sands from alluvial sources were extracted. This is not always the case, and many natural sands are blended with manufactured sand at the quarry before supply. The shape of this manufactured shape needs to be optimised and concrete producers need to have control tests to confirm this is consistent (Thomas et al 2007).

Research was undertaken in the 1960's and 1970's by the Ministry of Works and Prof. Harry Hopkins of the University of Canterbury that enabled laboratory assessment of the influence of particle shape of concrete sands (Hopkins 1971). The NZ sand flow test is now widely used internationally to characterize manufactured sands but is no longer widely used by local aggregate suppliers or in concrete production laboratories. Recently there has been the development of digital techniques that can quickly estimate particle shape from 0.5mm to 5mm. Also considered is the role of sand absorption and mineralogy on concrete performance and this can be assessed using techniques such as the Sika PCE slurry test method. A full summary of sand quality assessment includes several techniques that are summarised in Figure 1.

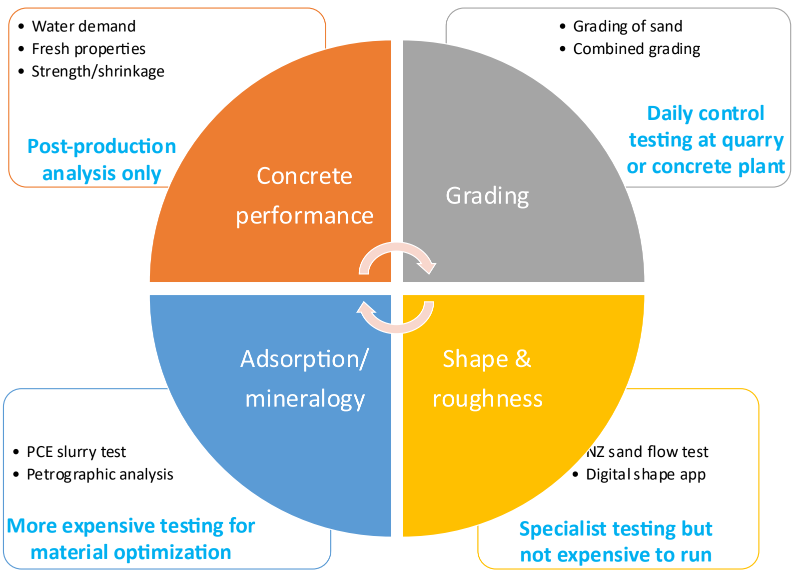

Figure 1: Methods of assessing sand quality for use in structural concrete

Quality control is mostly done using grading analysis of fine aggregate with occasional testing of cleanness and annual checks on density and absorption. Research has sometimes considered other factors such as particle shape but there appears limited data on the connection between sand quality and associated concrete performance in terms of cement efficiency or embodied carbon contents. International research has focused on improving manufactured sands with some studies looking at particle shape, including new efforts using the NZ sand flow test (Wu et al 2022, Pedersen 2011).

RESEARCH RELEVANCE

Before committing resources to improving sand quality, it is important to assess whether this will have any significant effect on cement efficiency. Analysing concrete production records it was possible to compare four different South Island plants with the following characteristics:

- First two readymix concrete plants (A & B) had improving sand quality with natural sands having consistent grading, low crusher content and were clean
- Second two readymix concrete plants (C & D) had deteriorating sand quality due to increasing crusher dust, more frequent episodes of lower cleanness, coarsening grading or deleterious fines and/or mica content

All four concrete plants had consistently good batching and testing control and used the same Portland cement, chemical admixtures and had no significant change in coarse aggregate quality over the time period. Changes in cement efficiency must therefore be at least in part related to changes in sand quality with these comparisons shown in Figure 2 (based on annual average values for grade 30 MPa concrete mixes). It should be noted that several other sands were compared with findings falling between the two extremes.

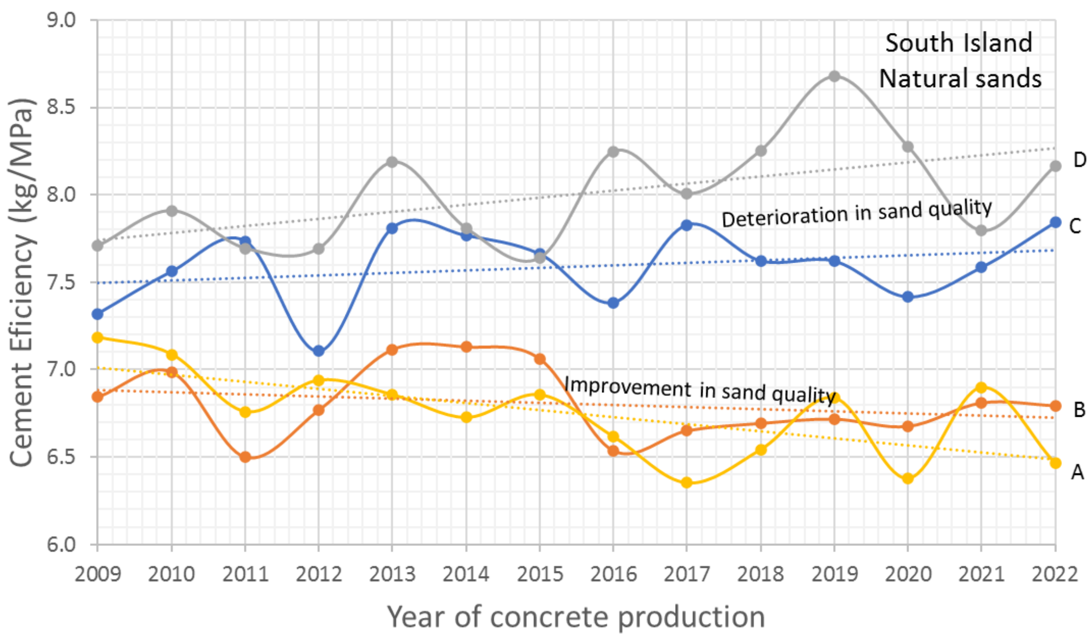

Figure 2: Comparison of cement efficiency of South Island concrete plants over 14 years

The comparison of cement efficiency shown above is more illustrative of extremes rather than the general standard. Nevertheless, it does show that significant cement savings or losses are possible when sand quality varies. Access to quality fine aggregate resources can allow at least 20% reductions of cement below typical values, with associated lower embodied carbon benefits. Investing in better quality aggregates can lead to overall savings in material cost even when this involves an increase of 50% in baseline prices (i.e. if optimum sand quality could be achieved by increasing material cost by 50% it is possible to save sufficient cement to achieve an overall saving in many cases).

This research focused on South Island natural sands as these are the materials mostly used by the author. There is a persistent view that sand quality is somehow immutably linked the local geology such that sands from alluvial sources will have lower water demand that leads to lower overall cement contents in concrete. While natural sand with rounded shape will generally produce concrete with lower water demands than manufactured sand, this does not fully explain difference in cementitious content. This is best illustrated by comparing across a range of materials from around New Zealand and comparing both water demand and water/cement ratio (shown in Figure 3).

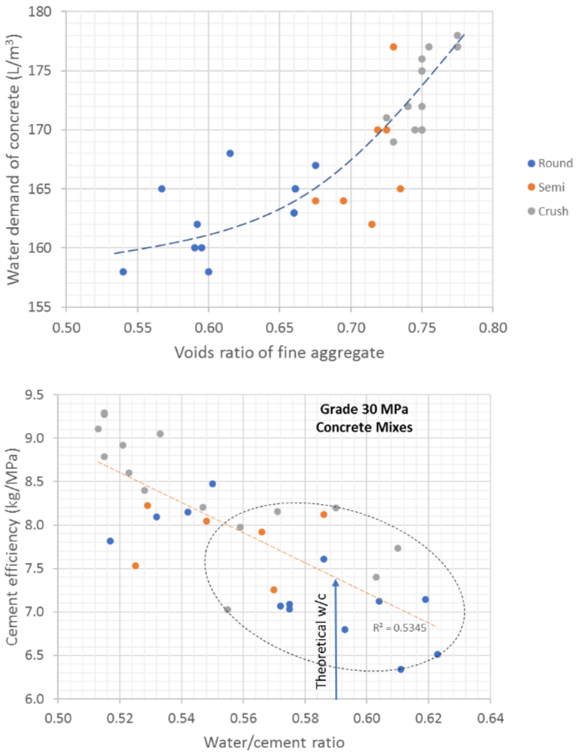

Figure 3: Comparison between water demands and water/cement ratios of NZ concrete

While the shape of sand particles influences water demand of concrete, this does not explain differences in water/cement ratio used to achieve compressive strength. Abram's Law states that water/cement ratio should provide an accurate estimation of 28 day strength but this not apparent in the above analysis. There must be other factors at play and this paper investigates what these might be and how to measure these practically.

EXPERIMENTAL PROGRAMME

A range of natural and manufactured sands were compared using the NZ sand flow test and a modern digital imaging technique (Sika Sand Analysis). These two methodologies (compared in Figure 4) use different approaches to estimation of particle shape, such that:

- NZ sand flow test is an empirical test method that measure the time required for a kilogram of sand to pass through a standard aperture of 12.7 mm diameter and the resulting voids content of material dropping into a set volume container
- Sika Sand method analyses the digital images of particles of sand and calculates the roundness and sphericity for each fraction of sand (from 0.5 – 5.0 mm).

This paper also presents data from the Sika PCE slurry tests that has recently been developed to assess the influence of aggregate adsorption and deleterious fines found in some natural and manufactured sands. The technique compares changes in mini-slump flow results for cementitious slurries with and without pre-soaking in a sample of fine aggregate and with and without filtering, with interpretation being based on guidelines developed by Sika R&D. Analysis of slurry testing can identify whether sand is prone to PCE adsorption or excess water adsorption from high fines.

Mortar strength trials were also undertaken using AS3583.6 where cement and sand were mixed with water until achieving a standard consistency (110±10 mm after flow table vibration of truncated cone sample) (Standards Australia 2018). The contribution of sand quality on overall cement efficiencies is also reviewed using concrete production data and laboratory trial data. The cement efficiency of different concretes was then compared with sand quality indicators such as NZ sand flow and digital techniques.

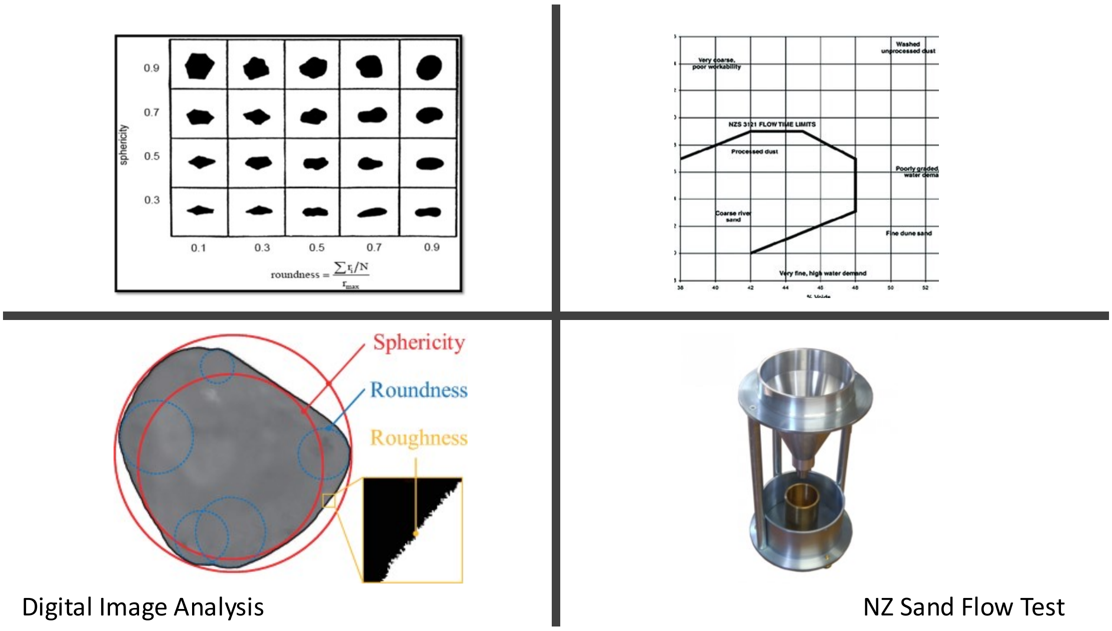

Figure 4: Comparison between particle shape analysis methods

SAND QUALITY ASSESSMENT

Initial assessment was undertaken on South Island natural sands used in concrete production from Invercargill to Nelson. Most of these sands have some level of crusher dust added at the quarry being preblended materials. As these sands were used without further blending at the concrete plant, the target grading was fairly consistent with fineness modulus of approximately 2.70. Table 1 compares a range of South Island concrete sands that were tested in 2022 and early 2023 using NZ sand flow testing and digital shape analysis (Sika Sand App).

Comparing these findings is difficult as both methods report two values making for a complex analysis. Nevertheless, some general trends can be identified with results being consistent with known proportions of crusher dust blending. Figure 5 shows some of this pattern in graphical form. This shows how sand flow times and voids content increase with better sphericity, where values below 0.4 are sub-angular to angular while values above 0.5 are more spherical.

The above analysis shows a reasonable correlation between the two techniques such that as the average sphericity or roundness decreases there is a consistent increase in flow time and void content. It should be noted however that the digital analysis uses a very small sample of approximately 5-10 grams, which makes sampling challenging especially if sand is dried before sampling. The analysis is not able to identify particles below 0.5 mm but this testing did show promise and the speed of analysis would be extremely useful for concrete readymix producers.

Table 1: Comparison of sand quality indicators of South Island materials

Location	**S.G.**	**F.M.**	**Flow time (secs)**	**Voids (%)**	**Sphericity**	**Roundness**
IV	2.70	2.60	19.6	33.3	0.68	0.59
GO	2.69	2.70	21.8	35.3	0.53	0.52
DU	2.72	2.85	25.5	44.5	0.40	0.43
CW	2.65	2.70	23.7	42.1	0.46	0.46
TI	2.68	2.75	22.3	39.5	0.66	0.57
AB	2.68	2.80	22.5	38.5	0.37	0.41
CH	2.65	2.72	21.3	35.3	0.55	0.53
ML	2.65	2.75	24.0	39.0	0.51	0.49
MI	2.65	2.75	22.8	37.6	0.54	0.52
GR	2.86	2.55	21.0	35.3	0.58	0.53
BH	2.72	2.80	22.1	37.8	0.45	0.54
NL	2.75	2.88	24.5	41.5	0.39	0.41

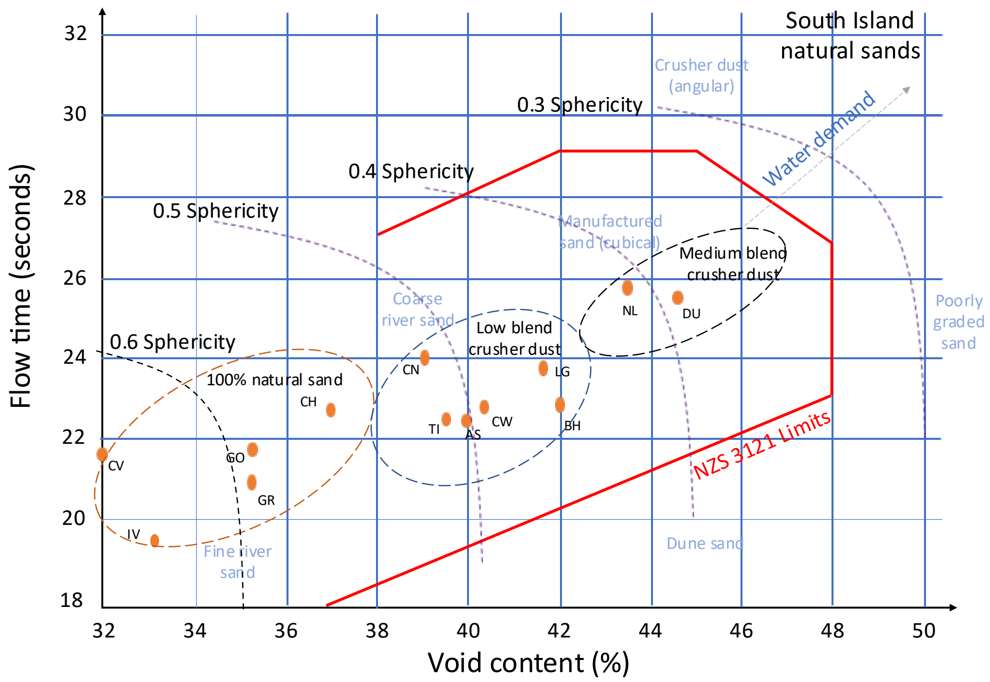

Figure 5: NZ Sand flow plotted with general range of average sphericity values

A summary of the results for slurry PCE trials and mortar testing is shown in Table 2 below for a limited range of concrete sands (note these are the same sands compared in Figure 2). Results show how these four sands may differ quite significantly due the following effects:

- Sands A & B were relatively clean, low porosity and consistently graded and showed no PCE adsorption, high fines and produced good strength
- Sand C was relatively dirty and porous and showed evidence of PCE adsorption and high fines but yet produced reasonable mortar strengths
- Sand D was relatively clean and well graded showing no PCE adsorption or deleterious fines but yet had consistently lower mortar strength

Table 2: Summary of PCE slurry and mortar testing of three natural sands

Property	**Sand A**	**Sand B**	**Sand C**	**Sand D**
PCE adsorption	No	No	Yes	No
High fines	No	No	Yes	No
Silt content (%)	7.0	6.0	13.0	7.5
Sand Equivalent	78	84	63	86
Water Demand (ml)	168	168	170	165
Mortar strength (MPa)	64.6	61.5	61.0	55.3

While the assessment of most sands was consistent and largely explainable, sand D was the exception since initial indications did not raise any particular concerns. This is an example of a material where more detailed analysis is required to identify possible deficiencies that may translate into poorer performance in practice. Petrography was able to identify the presence of micaceous elements that would affect workability and strength of concrete (Mackechnie 2003 & 2006).

It is possible to measure the biotite concentration by magnetic extraction from sand fines and research has shown that values above 2% start affecting strength quite significantly (Muller 1971, Micela 2017). Extraction of biotite from sand was successfully undertaken on the Three Gorge Dam project in China (Xue et al 2022). While full scale extraction may be challenging to implement in New Zealand, magnetic extraction could be used in the laboratory to identify potential issues when prospecting aggregate deposits sourced from metamorphic rock such as schist or gneiss.

CONCRETE PERFORMANCE CORRELATIONS

Concrete production data for South Island plants was analysed over the 2022/2023 period and cement efficiency of standard 30 MPa 19mm concrete mixes compared. Cement efficiency was expressed in terms of Portland cement per cubic metre of concrete divided by the average 28-day compressive strength in MPa. Cement efficiency was found to correlate best with voids content determined from the NZ sand flow test (see Figure 6) while other parameters showed a weak association.

Voids content is a measure of the packing efficiency of particles and is closely linked to loose bulk density. It is easy to measure either using the NZ sand flow apparatus of using a calibrated container such as the yield pot or smaller vessel. As shown above in Figure 6 this provides a reliable indication of overall particle shape and by implication of cement efficiency of concrete mixes.

The difference in embodied carbon between the best and worse performing concrete is sometimes as much as 60 kg/m^3, with a material cost difference of almost \$15/m^3. Hopefully these differences will be reduced when using SCMs such as fly ash or slag in concrete mixes (initial research shows this is likely fine SCMs used in NZ). Nevertheless, there is opportunity to reduce both emissions and costs by optimising resources and processing at quarries.

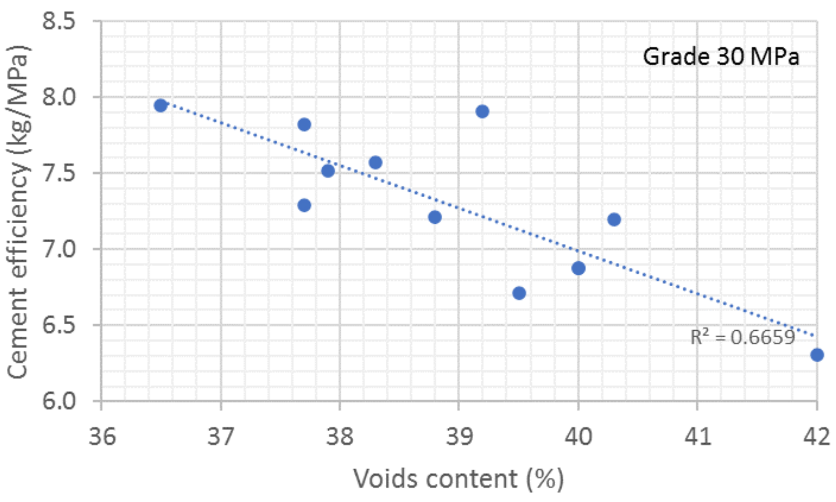

Figure 6: Cement efficiency of concrete production data versus voids content of sands

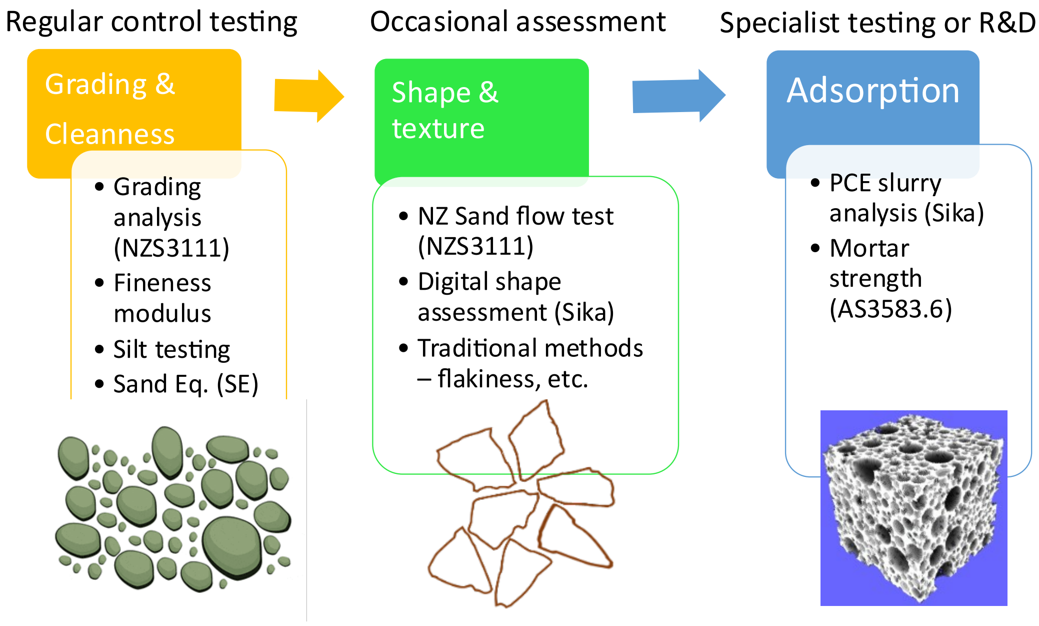

Figure 7: Suggested testing protocol of assessing sand quality

RECOMMENDATIONS

Testing reported in this paper is not sufficiently rigorous or wide-ranging to provide general recommendations for assessing the quality of sand used for concrete. Several new and quick techniques were trialled using mostly South Island sands and from this testing programme a tentative testing protocol has been developed. This is outlined in Figure 7 with more commentary also given below.

Grading

Particle size distribution is rightly considered to be important when producing either natural or manufactured sand for use in concrete. Unfortunately if this is the only quality metric it may result in poor quality concrete since particle packing and workability are affected by other properties listed below. Ideally all concrete producers should have access to a set of sand sieves to provide a daily or at least weekly record and allow more informed feedback to quarries.

Cleanness

The NZ standard NZS 3121 provides some useful guidance for natural sands in commentary clause C5.6 saying that sand equivalent (SE) should be above 80 and clay and silt content should be below 8% (Standards NZ 2015). Since SE value are only done at specialist laboratories and quarries it is useful for concrete suppliers to regularly undertake silt testing using the simple sedimentation test. The limitation of the silt or SE test is the type of fines is not assessed and more detailed analysis is recommended when assessing manufactured sand using either clay index or PCE slurry testing to differentiate between good fines (e.g. rock flour) and bad fines (e.g. silt or clay).

Shape

Particle shape is difficult to measure and even digital techniques have limited resolution of particles below 0.5 mm. Unfortunately the shape of fines in sand is important in the overall assessment. Older techniques such as the NZ sand flow test provide valuable information about changes in the shape or texture of sand and can be used as a reference value when new blends are being considered. Sands can be made with 100% manufactured material but it is important that crushing is optimised to produce cubical rather than angular shaped particles.

Deleterious fines

Some fines are not picked up with traditional techniques that focus on ultrafine particles such as silts or clays. Given the diversity of geology in New Zealand there are several other sources that may negatively affect concrete both in terms of workability and strength. Micaceous sands derived from schist, gneiss and granites are currently identified by petrographic analysis, which is slow and relatively expensive. More rapid techniques need to be developed to quickly highlight areas of concern before production of sand.

In all cases sand quality is most effectively controlled when concrete suppliers have simple tests that can identify potential issues before these escalate. At the moment only grading and cleanness can be done quickly but new techniques such as those investigated should become available to concrete producers.

CONCLUSIONS

Incremental savings in embodied energy of concrete require an understanding of all constituents within a concrete mix design. Figure 8 shows the different levels that can be achieved in practice provided there is an understanding of how to consistently achieve quality material. There must also be an awareness of how these materials affect performance not just of structural issues such as strength but also of secondary factors that affect serviceability.

Optimisation of materials for concrete requires simple quality assurance techniques that are able to measure inputs and these are correlated to the output in terms of concrete performance. This paper demonstrates some possible control techniques that can be easily used to assess sand quality. These modern techniques can complement existing techniques listed in New Zealand Standards such as NZS 3111 (Standards NZ 1986). While the economic cost of using extra cement has only been able to make a modest impact on improving sand quality, it is hoped that the environment cost will drive this process significantly further in the future.

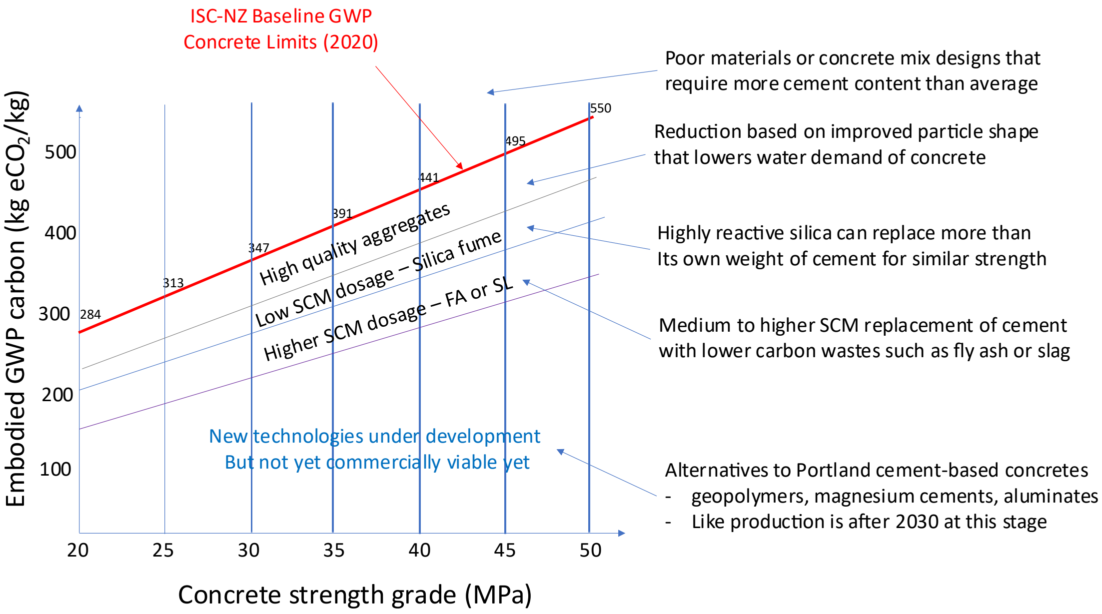

Figure 8: Range of possible embodied GWP found in NZ concrete

ACKNOWLEDGEMENTS

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