QUICK QUALITY CONTROL OF CONCRETE BLOCK PAVERS IN AUSTRALIA

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Summary

The present methods used in the control of concrete block pavers in Australia are tests such as compressive strength and abrasion resistance. Producers have found that the delay between paver manufacture and evaluation was excessive as data was unavailable to quickly address production problems. A much quicker method was required. One property which can be evaluated very early is "early life", or "green" bulk density. This property was investigated to determine if it was a reliable indication of paver quality. The 28 day compressive strength and abrasion resistance were also investigated and correlations between those properties and early density were found to be acceptable. The study was able to conclude that early paver bulk density could be used as a good estimate of the engineering serviceability properties of compressive strength and abrasion resistance.

Introduction

The paver quality indicators used most widely internationally are compressive and flexural strength (Canada, GFR, Japan, New Zealand, South Africa, USA). In Australian the individual mechanical properties typically studied have been compressive strength, abrasion resistance, flexural strength and skid resistance. Some useful work has been carried out in Australia on the mechanical properties of CBP (1, 2), but many unanswered questions remain concerning correlations between those properties. The relationships which have attracted the greatest attention are abrasion resistance/age of unit and compressive strength/abrasion resistance. These strength and durability based tests are generally only carried out after significant curing and are of little use in routine production quality control. Paver quality must be carried out immediately after paver production and one suitable and practical test would be density.

Paver Quality Control in Australia

Until 1980 there was no widespread accepted specification document in Australia for assisting with quality control of CBP production and supply. The Concrete Masonry Association of Australia (CMAA) published a specification document "Guide to Blocks" (MA15) in 1980 (3) which provided some guidelines for sampling and testing. Later the document "Specification for Concrete Segmental Paving Units" (MA 20) was published in 1986 (4) which contained an

interim guide for abrasion resistance testing which was based on wearing of the block surface with a ball race. More recently the "Draft Guide to the Specification of Concrete Segmental Units (MA34) (5) has been produced (Table 1) and MA34 is the most comprehensive Australian guide published to date. It includes requirements for properties such as dimensional deviations, flexural strength, abrasion resistance, skid resistance and salt resistance.

A big difference between MA34 and MA20 is the abrasion resistance test. MA20 prescribes the "Ball Race Test", developed by Perth City Council as a modified version of ASTM C779-82, while MA34 specifies the use of the "Tumbler Test", developed by Sydney City Council. The test involves tumbling steel balls against the paver's surface. MA34 also recommends that compressive strength be replaced with a flexural strength test, considered to be a better quality indicator as it is not affected by thickness of the test sample. The MA20 compressive strength test and abrasion resistance tests however are still used widely for acceptance.

Table 1. CMAA draft specifications

Property	CMAA draft specification
Plan dimensions	2 - 3 mm (SD)
Thickness	3 mm (SD)
Characteristic flexural	2 - 4 MPa
Characteristic break	2 - 10 kN
Skid resistance	0.4
Tumbler abrasion index	3.5 - 7

1 SD refers to the maximum standard deviation in dimension

Planning the Investigation

The main aim of the study was to test the use of green (wet) density of pavers immediately after production, as a simple but effective method of controlling quality on an operational basis. This would allow production managers or supervisors to quickly make appropriate adjustments for any excessive deviation in quality of units. Ideally the period for evaluation should not exceed a few minutes so that the amount of any defective product would be very small. Investigation was also carried out to test for correlation between the various mechanical properties specified in MA20 and MA34

Paver mechanical properties such as compressive strength, flexural strength, durability are all dependent to some amount, on density (6). Thus if the density of a unit can be accurately determined then other properties should be able to be estimated provided that mix proportions and raw materials do not vary significantly. Paver density development with time was studied then and then density used as a factor in the study of mechanical properties such as compressive strength and abrasion resistance. A lower bound value for acceptable fresh density would provide a very powerful quality control tool, enabling a block manufacturer to make rapid changes to remedy deficient production.

Paver Testing Program

The testing program was devised to achieve the following tasks.

- To determine abrasion resistance (ball race) development of CBP with curing time and to investigate any correlation with compressive strength.
- To identify how the moisture content of CBP at testing affects compressive strength over a spectrum of curing times.
- To study the development of density of CBP over a 28 day curing period and establish a relationship between early life (green) density and 28 day density.
- To identify any correlation between 28 day compressive strength and 28 day density and between 28 day abrasion resistance and 28 day density.
- To determine the relationship between wet density and 28 day density, 28 day compressive strength and 28 day abrasion resistance.
- To establish minimum acceptable wet densities of pavers, which could be used to ensure that compressive strength and abrasion resistance specifications were achieved.

Experimental Work

Development of CBP Compressive Strength with Air Curing

The objective was to determine the typical development of concrete paver compressive strength with air curing time to gain an idea of the pattern of compressive strength growth and what would be a suitable age for compressive strength testing. Air curing was adopted to model the typical, uncontrolled conditions which occur under real production situations.

Pavers used for this test were interlocking pavers with a thickness of 60 mm, produced by Besser Pioneer. Pavers were cured overnight using mist curing. Raw material characteristics and the mix grading are provided elsewhere (2). Pavers (200) were randomly sampled over one shift such that the "lot" represented a full shift's production. Units were stored in an air conditioned laboratory environment (20°C +/- 2°C). Weight, height, volume, density and compressive strength were determined daily for air curing periods up to 28 days and then at 40, 62, 90, 150 and 183 days. Compressive strength tests were conducted on lots of 5 pavers in accordance with MA20, using equation 1. The results did not show good correlation and are available elsewhere (2).

$$C = \left(\frac{W}{A}\right) \cdot \left(\frac{5}{\sqrt{A} \,/\, (H+1.87)}\right) \qquad \ldots\ldots (1)$$

where C = compressive strength in MPa
W = total failure load, N
H = nominal height of specimen, mm
A = nominal gross plan area, mm^2

The Effect of Test Moisture Condition on Compressive Strength

MA20 does not specify sample moisture condition for compressive strength. Three groups of 8 pavers, 30 days old, were taken from the same mix. A dry density range of 2100 to 2165 kg/m^3 was used to reduce strength variability caused by density effects (Table 2). Different paver groups were then immersed into tap water for 24 hours, a drying oven (temperature 105°C)

and in the laboratory environment (20°C +/- 2°C), for 24 hours. The pavers were then tested for compressive strength and results are summarised in Table 2.

Table 2. Effect of moisture condition on compressive strength

Water soaked		Oven dried		Ambient	
Density (kg/m^3)	Strength (MPa)	Density (kg/m^3)	Strength (MPa)	Density (kg/m^3)	Strength (MPa)
2154	44.3	2157	55.2	2145	52.2
2127	41.0	2128	52.2	2165	52.1
2164	47.3	2143	50.2	2155	54.5
2145	43.8	2093	45.1	2138	52.9
2140	44.9	2143	51.2	2120	45.3
2120	39.1	2124	51.9	2140	52.6
2134	43.3	2138	54.6	2109	47.1
2118	41.1	2155	51.9	2133	46.4
2138[1] (1%)[2]	43.1 (6%)	2135 (1%)	51.5 (6%)	2138 (1%)	50.7 (7%)

1 Mean values of density and strength for the 8 paver set
2 Coefficient of variation of paver set

The Development of Abrasion Resistance with Curing Time

The compressive strength of concrete develops as the hydration processes proceed. At the beginning it is controlled by the hydration of cement mineral alit (C_3S) and in later stages by belit (C_2S). These processes control "macro" abrasion resistance of thick sections but do not entirely apply for paving units. The pavers' abrasion resistance is largely a function of the upper surface layer of cement and aggregate. The decisive factors will be cement content, stage of hydration (which is affected by curing regime), type of curing and degree of carbonation. It is still not clear, if and how, the abrasion resistance of concrete pavers develops with curing time.

Paving units from the compressive strength tests described earlier, were used to investigate abrasion resistance development with curing period. Abrasion resistance was evaluated using the MA20 abrasion index test. The number of units used for each test lot was 5 although it is recognised (1, 2) that 10 pavers are preferred for better statistical accuracy. Pavers were tested at the age of 1, 3, 7, 15, 21, 28, 40, 60, 90, 150 and 180 days. Abrasion index was calculated using equation 2 and results are summarised in Figure 1. The regression line suggests that there is an increase in abrasion index with paver age.

$$I_a = \frac{\sqrt{R}}{P} \qquad \ldots\ldots (2)$$

where I_a = abrasion index
R = ball-race revolutions in thousands
P = penetration in millimetres

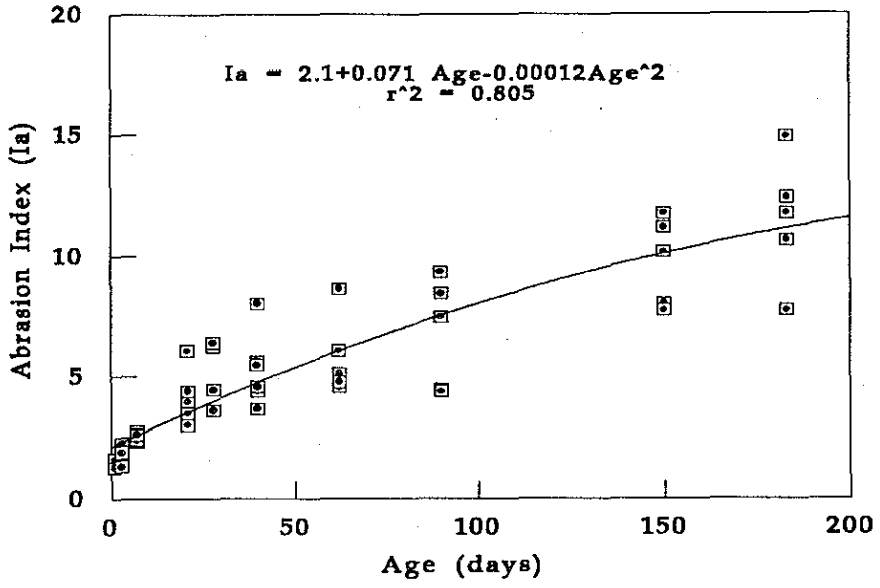

Figure 1. Increase of abrasion index with age

Density Development with Air Curing Age

Paver density can be an important indicator of strength and abrasion resistance. It is desirable to be able to predict 28 day density of pavers using the immediate post production or "green" density. This possibility was studied using the density of units at 2 minutes after production, at the corresponding 28 day (of air curing) density, and again at various ages up to 60 days. Nine sets of pavers, with 5 pavers in each set, were randomly sampled from the production. The results are summarised in Table 3 .

Table 3. Paver density variation with air curing age

Sample Lot	Paver density (kg/m^3)						
	0 day	1 days	3 days	7 days	14 days	28 days	62 days
1	2194	2151	2142	2140	2136	2136	2131
2	2213	2172	2162	2161	2156	2156	2151
3	2225	2183	2173	2172	2168	2168	2164
4	2253	2211	2201	2199	2194	2194	2190
5	2192	2149	2140	2136	2132	2132	2126
6	2184	2141	2133	2128	2124	2124	2122
7	2227	2183	2177	2173	2168	2168	2165
8	2194	2151	2143	2139	2134	2134	2131
9	2211	2163	2154	2152	2146	2146	2143
Mean %[1]	100	98.0	97.7	97.5	97.4	97.2	97.2

1 Expressed as a percentage of initial or "0" day density

Correlating Density and Compressive Strength (Air Curing)

The correlation between paver density and compressive strength, after 28 days air curing, was investigated. Pavers were randomly sampled from production over a period of several months. Two aggregate/cement ratios were used during the sampling period however only the data for heavy duty pavers is reported here as their quality is generally considered of greater importance. The materials were the same as those described earlier. Both rectangular and interlocking pavers were sampled. After overnight mist curing, pavers were placed in the laboratory environment.

After 28 days of laboratory curing, density, moisture content and compressive strength were determined. The correlation between density and compressive strength was explored and the results are summarised in Figure 2. Good correlation (r^2 = 0.845) was found between 28 day compressive strength and paver density. The sampling technique used ensured that all production variables were included in the analysis.

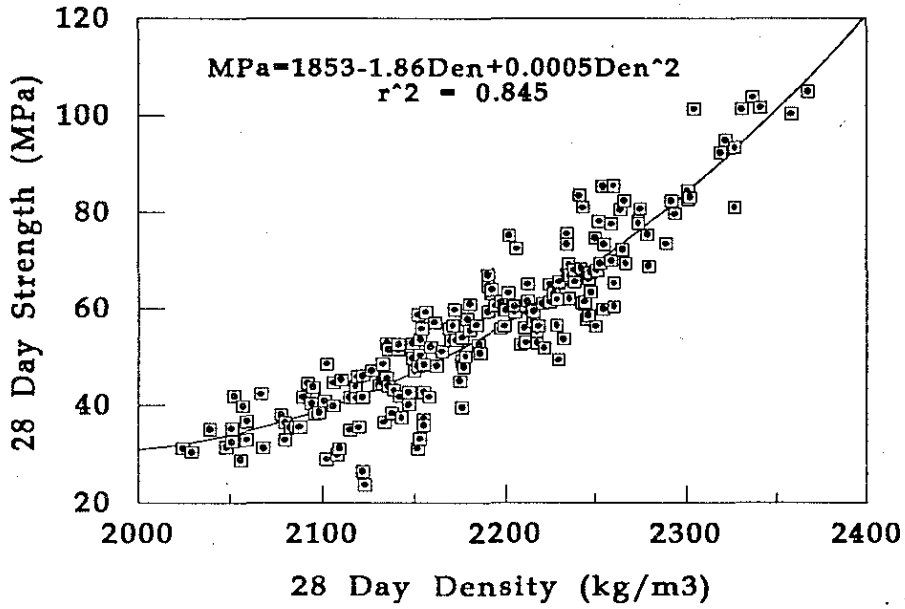

Figure 2 Density and compressive strength at 28 days.

Correlating Density and Tumbler Abrasion Resistance (Air Curing)

The new MA34 abrasion resistance guideline, based on the tumbler test was investigated and related to early life density and 28 day density. Over 80 pavers from 4 identical mix designs were sampled and tested after 28 days of laboratory curing for moisture content, density and tumbler abrasion resistance. Abrasion resistance is expressed as loss in paver volume (in cm^3), which is caused by the impact and rolling action of the steel ball bearings (Figure 3).

Previous work using the tumbler test has indicated that good correlation could be expected between it and mechanical strength properties. The test does not suffer from errors initiated by ball race seating time, water flow to the ball race and the age of balls, in the ball race test (1, 2). The question still remains however, which of these two tests better represents field behaviour.

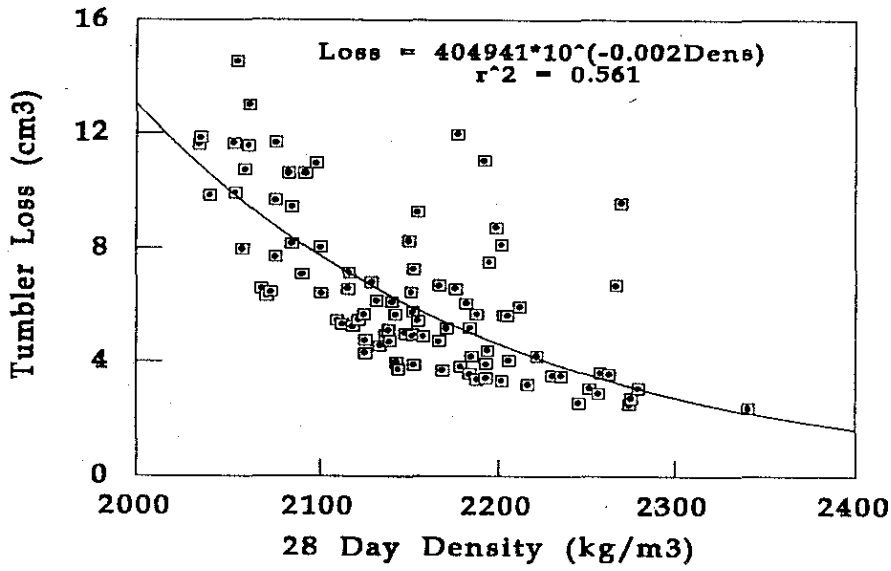

Figure 3. Density and abrasion resistance

Analysis of Test Data

Strength Development with Air Curing

Increase in compressive strength became minimal after the age of seven days when paver void saturation level fell below that required for hydration. This indicates that a 7 day test should provide sufficient information on 28 day compressive strength, based on laboratory air curing. The pattern of strength growth will likely be different for fully air-cured products (no misting).

Abrasion Index (Ball Race) Development

Figure 1 indicates that development of abrasion resistance (rotating ball race) increased continually with curing time, although compressive strength increase had almost ceased after 7 days. Abrasion resistance is probably affected by variables such as cement content, curing regime and carbonation, all of which can influence the condition of the top surface layers.

The Effect of Moisture Content

There was a significant difference in the compressive strengths of the 3 lots of pavers tested at the different moisture conditions. The pavers tested after being immersed for 24 hours in water yielded significantly lower test results compared to those conditioned in the laboratory environment or oven dried at 105°C (Table 3). The results from units conditioned under ambient laboratory conditions were comparable to those obtained from oven-dried specimens.

Time for Attaining Density Equilibrium

Paver density followed a good trend of bulk density decrease with storage time. Weight dropped over a 28 day period by about 2.8 %, due to evaporation of water and the hydration processes. After about 28 days, density became relatively constant, being affected only very slightly by changes in relative humidity in the laboratory. Density at 28 days was considered to have reached equilibrium with the laboratory environment and was predictable using green

density. Early density can then be correlated with 28 day compressive strength and abrasion resistance.

Correlating Compressive Strength and Paver Density (Air Curing)

Figure 2 shows the good correlation between 28 day compressive strength and 28 day densities. The linear regression equation is comparable to results obtained from similar studies conducted elsewhere (6). The information presented suggests that a lower bound level exists which should be easily achieved and also be economical and desirable from the compressive strength view. A minimum compressive strength of 50 MPa to 60 MPa is usually required for individual heavy duty pavers for comfortable achievement of the MA20 specified 45 MPa minimum characteristic strength. Once a correlation between paver strength and density is determined as shown in equation 3, an expression for a desired target strength can be established as shown in equation 4.

$$R_{28} = a.D_{28} + b \qquad \ldots\ldots (3)$$

then using (3)

$$Rt_{28} = k.a.10^6.\frac{W}{(A.H)} + b \qquad \ldots\ldots (4)$$

Hence the desired "fresh" weight of any paver should be at least:

$$W = \frac{(Rt_{28} - b).A.H}{k.a.10^6} \qquad \ldots\ldots (5)$$

where R_{28} = the 28 day compressive strength (MPa)
a,b = coefficients of linear equation
D_{28} = 28 day density (kg/m^3)
Rt_{28} = target 28 day compressive strength (MPa)
k = coefficient expressing relationship 28day density-fresh density
W = weight of a green paver (g)
A = area of paver (mm^2)
H = height of paver (mm)

In Table 4 an example from one Queensland production plant is shown. For each product, several heights are included due to the minor variation in product height. The unit is taken in its fresh stage, supported by a pre-weighed plastic plate and its weight and height measured. The weight is then assessed according to Table 4 and appropriate action can be taken if necessary.

Abrasion Resistance and Density Correlation

Although the correlation between density and compressive strength is very good, that between abrasion resistance (tumbler test) and density is relatively poor. From Figure 3 it can be seen that this tumbler loss tends to become relatively constant at a paver density of about 2200 kg/m^3. Using the MA 34 (Table 1), indexes range from 3 to 7.5 with a value of 5 used for

roadways and industrial pavements. The best range of densities for an index of 5 lie (on the regression line) between 2220 kg/m^3 and 2250 kg/m^3. If tumbler index and density are plotted against the compressive strength (Figure 4) the density range of 2220 -2250 kg/m^3 appears to be a good target, both for abrasion resistance (index of 5) and compressive strength (55 MPa). This approach has been recognised in Canada (7) where for average compressive strength of 50 MPa, a minimum unit weight of 2195 kg/m^3 is specified.

Table 4. Rapid quality control

Product	Height (mm)	Weight (kg)	Wet Density (kg/m^3)	1D Density (kg/m^3)	28D Density (kg/m^3)	Est R28 (MPa)
ILK 80	78	4.42	2300	2254	2235	65.5
ILK 80	79	4.48	2301	2255	2237	65.9
ILK 80	80	4.53	2298	2252	2234	65.2
ILK 80	81	4.59	2300	2254	2235	65.5
FGSTONE	188	3.98	2228	2184	2166	50.6
FGSTONE	189	4.00	2228	2183	2165	50.5
FGSTONE	190	4.02	2227	2183	2165	50.3
FGSTONE	191	4.04	2227	2182	2164	50.2

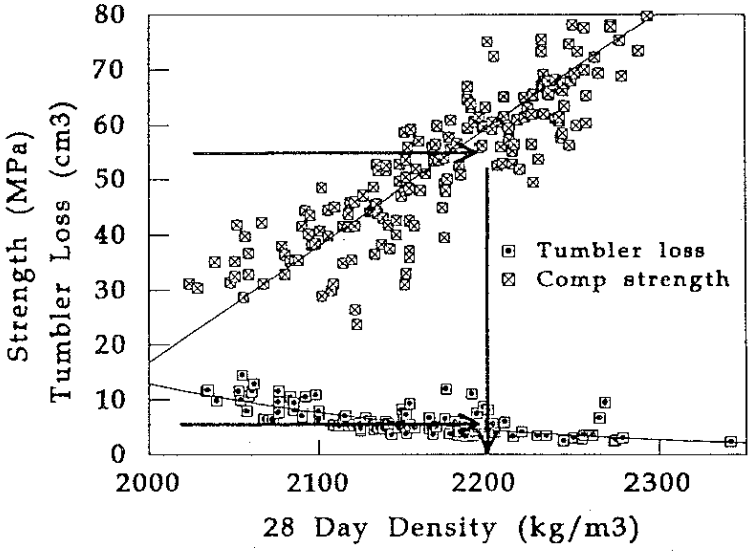

Figure 4. The good quality chart

Discussion

Although there are no requirements for minimum compressive strength in MA34 this property is still widely used as a quality control measure. The use of green density as an early quality indicator should be a very helpful, and additional tool, which allows early detection and

elimination of production problems. As flexural strength replaces the compressive strength test with the adoption of MA34, it should still be possible to use the green density quality control method as compressive strength can be well correlated with flexural strength (6). A similar view of the use of density as a good quality indicator has also been reported by others (8, 9, 6).

Conclusion

A very good correlation was found between fresh density of pavers, 28 day density and 28 day compressive strength of the same specimens. A correlation between density and abrasion resistance of paving units using the MA34 tumbler test was also determined. The green (2 minute) density of concrete pavers was found to be a very good routine production quality control tool.

There was no significant difference between compressive strength test results obtained from specimens tested oven dry or with ambient moisture content. The development of compressive strength of overnight mist cured followed by air curing concrete pavers was determined. The strength increased up to 7 days and then remained fairly constant. Abrasion index measured on units from the same lot of pavers continued to increase at ages above 180 days. This confirmed that abrasion resistance was not a function of compressive strength.

It would be worthwhile to consider the implementation of minimum density requirements for concrete pavers as part of quality control. Measurement of density is very easy, cheap and effective. The adoption of this simple means of good production quality control will allow block producers to increase quality at low cost. The good correlation between density and compressive strength can be considered to generally apply, but each producer who intended to use this type of quality control would need to establish their own correlation due to different raw materials and other variables.

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