Asessing the Compressive Strength Properties of Semi-Flexible Pavements

A. Setyawan*

*Department of Civil Engineering, Sebelas Maret University, Indonesia

Abstract

Semi-flexible pavements are manufactured by producing a very open porous asphalt skeleton and filling the voids with selected cementitious grouts. The resultant composites, referred to as "grouted macadams", combine the flexibility of the bituminous component with the strength and rigidity of the cementitious component. Grouted macadams thus combine the best qualities of concrete and asphalt pavements, namely the flexibility and freedom from joints that characterize asphalt and the high static bearing capacity and wear resistance of concrete. The properties of the grouted macadam composites were assessed using a range of engineering, compressive strength is the most common strength test for rigid pavements since it is relatively easy to conduct compared to other tests and numerous correlations exist to predict other material properties based on compressive strength values. Since semi-flexible pavements possess mechanical properties in between bituminous mixtures and concrete, the compressive properties of the grouted macadams designed in this study have been investigated. The unique correlations between each component, namely asphalt skeleton, grout, aggregate type and size were established also the comparison to the other type of investigations and conventional concrete.

Keywords: Compressive strength; grouted macadam; semi flexible pavement.

1. Introduction

Compressive strength properties are routinely used to characterize concrete materials, this type of test is taken to be the main indicator of concrete quality. In rigid pavement design, the tensile and flexural strengths are the critical properties that characterize the materials since these materials are generally much stronger in...
compression than in tension and the nature of the loading conditions will create tensile failure prior to compressive failure. However, compressive strength is the most common strength test for rigid pavements since it is relatively easy to conduct compared to other tests and numerous correlations exist to predict other material properties based on compressive strength values (Carrasquilo 1994, Mindess & Young 1981). Since semi-flexible pavements possess mechanical properties in between bituminous mixtures and concrete, the compressive properties of the grouted macadams designed in this study have been investigated and the results presented in this paper.

2. Compressive Strength

2.1. Sample preparation and procedure

Compressive strength tests were carried out in accordance with BS 1881: Part 116: 1993. Cubes of 100×100×100mm were prepared for compressive strength testing at 1, 7 and 28 days. The tests were carried out at room temperature with a constant rate of loading of 3 kN/second.

2.2. The effect of cementitious grout

The effects of varying the type of cementitious grout were investigated using hot limestone porous asphalt (HLPA) grouted macadam specimens that were filled with four types of cementitious grouts (Hassan et al, 2002). Three types of cementitious grouts were developed and tested in this investigation in addition to a commercial grout (Pozament) that was kindly supplied by Tarmac Northern Ltd. The compressive strength test results are presented in Table 1 and graphically illustrated in Figure 1.

| Material         | Compressive strength (MPa) |
|------------------|----------------------------|
|                  | 1 day curing | 7 days curing | 28 days curing |
| HL/OPC-GM        | 8.77          | 11.80          | 11.85          |
| HL/SF-GM         | 8.82          | 10.76          | 13.82          |
| HL/FA&S-F-GM     | 7.18          | 9.66           | 13.71          |
| HL/Poz-GM        | 8.71          | 11.07          | 13.82          |
Figure 1. Compressive strengths of grouted macadams with different grout types

At early age (1 day) both the OPC and SF grouted macadams gave higher strengths than the FA/SF specimens. The Pozament grouted macadams gave comparable values to the OPC and SF grouted macadams. However, the beneficial effect of cement replacement materials was clearly demonstrated at later ages. Fly ash (FA) and silica fume (SF) are known to improve the packing capacity of the composite due to their particle shape, fineness and pozzolanic properties, which in turn results in improved pore structure of the composite. At 28 days, the compressive strengths of SF and FA/SF grouted macadam were almost identical at 13.82 and 13.71 MPa for the SF-GM and FA/SF-GM, respectively, and about 15% higher than that of OPC-GM. The Pozament grouted macadam had a similar strength development to that of SF-GM.

The influence of cementitious grout strengths on the strength of the resultant grouted macadams are presented in Figure 2. All the grouted macadams were produced using a hot limestone porous asphalt (HLPA) which on its own, had an average compressive strength value of 1.69 MPa.
Figure 2. Typical correlation between the compressive strength of cementitious grout and its respective grouted macadam

The typical correlation between the strengths of cementitious grouts and their respective grouted macadam is shown in Figure 2. The equation of the linear regression line using the strength of the porous asphalt as an intercept, is as follows:

\[ F_{c-gm} = a + b F_{c-grout} \]  \hspace{1cm} (1)

where: \( F_{c-gm} \) = compressive strength of grouted macadam, \( a \) = compressive strength of Porous asphalt, \( b \) = The slope of the linear regression, \( F_{c-grout} \) = compressive strength of the grout.

Based on the correlation typically presented in Figure 2, the linear regression equations for all types of grouted macadam are presented in Table 2.

Table 2. Correlation between strength of cementitious grouts and their respective grouted macadams

| Type of specimen | Equation                  | \( R^2 \) |
|-----------------|--------------------------|----------|
| OPC             | \( F_{c-gm} = 0.1053 F_{c-grout} + 1.69 \) | 0.66     |
| SF              | \( F_{c-gm} = 0.1066 F_{c-grout} + 1.69 \) | 0.74     |
| FA/SF           | \( F_{c-gm} = 0.1304 F_{c-grout} + 1.69 \) | 0.79     |
| Pozament        | \( F_{c-gm} = 0.1042 F_{c-grout} + 1.69 \) | 0.91     |

Except for the Pozament mixture, the correlation coefficients were not very satisfactory. Taking all the data into consideration as shown in Figure 3, the compressive strength of a grouted macadam with a hot porous asphalt skeleton (1.69 MPa compressive strength), can be predicted from the compressive strength of its hydrated grout using the following linear regression correlation (\( R^2 = 0.67 \)): 
\[ F_{c-gm} = 0.1084 F_{c-grout} + 1.69 \]  

(2)

where: \( F_{c-gm} \) = compressive strength of grouted macadam, \( F_{c-grout} \) = compressive strength of the grout.

On average, at full curing, the strengths of the grouted macadams were approximately 11% of the compressive strengths of their respective hydrated cementitious grouts.

\[ F_{c-gm} = c \times F_{c-grout}^d \]  

(3)

where: \( F_{c-gm} \) = compressive strength of grouted macadam, \( c \) = constant, \( d \) = the slope of the power regression, \( F_{c-grout} \) = compressive strength of the grout.

Table 3. Correlation between strength of cementitious grouts and their respective grouted macadams using a power relationship

| Types of specimens | Equation \( F_{c-gm} = \) | \( R^2 \) |
|--------------------|--------------------------|--------|
| OPC                | \( 1.1756 \times F_{c-grout}^{0.5017} \) | 0.99   |
| SF                 | \( 0.8409 \times F_{c-grout}^{0.5792} \) | 0.82   |
| FA/SF              | \( 1.3432 \times F_{c-grout}^{0.4946} \) | 0.88   |
| Pozament           | \( 0.6339 \times F_{c-grout}^{0.6396} \) | 0.95   |

The power regression lines gave higher correlation coefficients. However, these did not take into account the original strength of the porous asphalt skeleton. A generalized relationship for all hot mixture grouted macadam is given in Equation 4 (with a correlation coefficient of 0.83) and graphically displayed in Figure 4.
For practical applications, equation (4) could be simplified as follows:

$$F_{c-gm} = 1.35 \times F_{c-grout}$$ \hspace{1cm} (5)

where: $F_{c-gm} =$ compressive strength of grouted macadam, $F_{c-grout} =$ compressive strength of the grout

![Figure 4. The correlation between the compressive strength of the cementitious grouts with their respective grouted macadam in power regression](image)

### 2.3. The effect of bitumen type

The effect of bitumen type on the compressive strength properties of grouted macadams was investigated using two types of porous asphalt skeletons, i.e. a hot limestone porous asphalt (HLPA) and a cold limestone porous asphalt (CLPA). Both skeletons were filled with identical silica fume cementitious grouts (SF). The test results are presented in Table 4 and graphically displayed in Figure 5.

| Material  | Compressive strength (MPa) | 1 day curing | 7 days curing | 28 days curing |
|-----------|-----------------------------|--------------|---------------|----------------|
| HL/SF-GM  |                             | 8.82         | 10.76 (22%)   | 13.82 (57%)    |
| CL/SF-GM  |                             | 5.09         | 9.11 (79%)    | 11.99 (135%)   |
At all curing ages up to 28 days, the compressive strengths of CL/SF-GM were lower than those of HL/SF-GM. This was attributed to the lower strength of the cold mixture porous asphalt skeleton. However the CL/SF-GM showed a higher rate of compressive strength development compared to the HL/SF-GM. In a hot mixture grouted macadam, the strength development was purely dependent on the strength gain of the cementitious grout.

2.4. The effect of aggregate types

The effect of aggregate type on the compressive strength of grouted macadam was investigated by producing two types of cold mixture grouted macadams with a carboniferous limestone (CL/SF-GM) and a dolomitic limestone (CD/SF-GM). Both porous asphalt skeletons were grouted using an identical silica fume (SF) cementitious grout. The test results are presented in Table 5 and graphically illustrated in Figure 6.

Table 5. Compressive strength of grouted macadam with different types of aggregates

| Material     | Compressive strength (MPa) |
|--------------|-----------------------------|
|              | 1 day curing | 7 days curing | 28 days curing |
| CL/SF-GM     | 5.09          | 9.11 (79%)    | 11.99 (136%)   |
| CD/SF-GM     | 3.63          | 7.33 (102%)   | 9.80 (170%)    |

* values in brackets indicate the percentage increase in strength compared to 1 day results.
The test results indicate that the compressive strengths of grouted macadam were significantly influenced by the strength properties of the aggregates. Dolomitic limestone aggregates (TFV = 90 kN) have approximately 60% of the crushing strength of Carboniferous limestone (TFV = 150 kN). As a consequence, the dolomitic limestone grouted macadams had approximately 80% of the strength of the carboniferous limestone grouted macadams. The rate of strength gain of CD/SF grouted macadams were slightly higher than CL/SF grouted macadams as shown in the Figure 6 in brackets in Table 5.

![Figure 6. Compressive strength of grouted macadam with different types of aggregates](image_url)

2.5. Relation between compressive strength of porous asphalt and the resultant grouted macadam

The relationship between the strength of porous asphalt skeletons and their respective grouted macadams was also investigated. Three types of porous asphalts: HLPA, CLPA and CDPA, were filled with an identical cementitious grout (SF) and were subsequently tested at different curing ages. The test results are presented in Figure 7.

In the case of hot mixture porous asphalt skeletons, full skeleton strength was achieved soon after cooling down to the ambient temperature. Any further strength development was fully governed by the hydration of the cementitious grouts.

For the cold mixture porous asphalt skeletons, strength would have continued to develop as curing progressed, provided the water from the asphalt emulsion and any pre-wetting was allowed to escape. Since the grout filling process was carried out 24 hours after compacting the asphalt, the cold mixtures porous asphalt would not have had time to achieve their ultimate strengths. The presence of a cementitious grout surrounding the bitumen coated aggregate particles of the porous asphalt skeleton would have undoubtedly affected the strength development of the cold skeleton. Simultaneously, the presence of excess water from the cold mixture porous asphalt may
have affected the hydration process of the cementitious grout. However, this phenomenon was not examined in detail and deserves a more thorough investigation.

The compressive strengths of the cold mixture porous asphalt skeletons with different aggregates types were not reflected in the compressive strengths of their respective grouted macadams. The CLPA skeleton which had lower compressive strength than CDPA resulted in a grouted macadam with higher compressive strength value. The higher compressive strength of the CDPA skeleton (containing the weaker dolomitic limestone aggregates) compared to the CLPA skeleton (containing the stronger limestone aggregates).

It becomes evident that for the cold mix grouted macadams, the compressive strengths were more dependent on the crushing strengths of the aggregates than the compressive strength of the porous asphalt skeleton (which is predominantly governed by the binder adhesive and cohesive properties).

There is a relation between the strength development of the cold mixture porous asphalt skeleton and the strength development of the cold mix grouted macadam as graphically displayed in Figure 7. However, the role of the porous asphalt skeleton in influencing the fully cured compressive strength of the composites was not very clear. The relationship between compressive strength of cold mix grouted macadams and the silica fume grout could be expressed in Equation 6 ($R^2 = 0.99$).

$$F_{c-gm} = 16.72 \times F_{c-clpa}^{1.5374}$$  \hspace{1cm} (6)

where: $f_{c-gm}$ = compressive strength of grouted macadam, $f_{c-clpa}$ = compressive strength of cold limestone porous asphalt.

This equation is only valid for cold mixture grouted macadam produced with a silica fume cementitious grout.
2.6 **Comparison of compressive properties with other investigations and with concrete**

The compressive strength values of the various grouted macadams investigated were compared with results reported in earlier investigations and with typical results from concrete as shown in Table 6 and Figure 8.

Table 6. Compressive strengths of grouted macadam and concrete

| Material                  | Compressive strength (MPa) |
|---------------------------|----------------------------|
|                           | 1 day curing | 7 days curing | 28 days curing |
| HL/OPC-GM                 | 8.77         | 11.80         | 11.85         |
| HL/SF-GM                  | 8.82         | 10.76         | 13.82         |
| HL/FA&SF-GM               | 7.18         | 9.66          | 13.71         |
| CL/SF-GM                  | 5.09         | 9.11          | 11.99         |
| CD/SF-GM                  | 3.63         | 7.33          | 9.80          |
| HLL/M-GM                  | 14.76        | 18.79         | 21.36         |
| HLG/M-GM                  | 11.46        | 14.07         | 18.29         |
| (1)RMP                    | n/a          | n/a           | 3.869         |
| (2)Densiphalt             | 5.50         | 7.00          | 7.00          |
| (1)Concrete (Plain)       | 19.56        | 34.60         | 48.1          |
| (1)Concrete (50% FA)      | 5.62         | 31.85         | 57.00         |

(1)Andertoon 2000, (2)Collop & Elliott 1999, (3)Atis 1995

Figure 8. Compressive strength of various grouted macadam and concrete
All the grouted macadam types designed in this investigation performed better in terms of compressive strength at 7 and 28 days compared to other grouted macadam composites (e.g. Densiphalt and RMP). The lower compressive strengths of cold mixture grouted macadams at 1 day curing were caused by the weakness of the 24 hour cured cold mixture porous asphalt. By the time the strength of the cold mix skeleton was reasonably developed, the cold mixtures attained very acceptable compressive strength values.

Compared to RMP, which are produced using a similar bitumen type and content, the 28-days compressive strength of hot mix grouted macadams developed in this investigation were about 300% higher. The cold mix grouted macadams also gave higher strengths than the RMP. The main reason is that the compressive strengths of the SF grouts were much higher (108MPa) compared to the resin modified grout (22.8MPa).

Densiphalt gave high early age strengths, similar to the hot mix grouted macadams designed in this investigation. However, the ultimate strength of Densiphalt at 28 days curing was lower than either the hot or cold mix grouted macadams. The Densiphalt mixture used a proprietary cementitious grout (referred to “Densit” containing a microsilica mortar) with a compressive strength value of (135MPa) which was not dissimilar to the compressive strength of the OPC/SF grout (108MPa) used in this investigation. On the other hand, the porous asphalt skeleton used for Densiphalt was produced using a softer (200 penetration grade) bitumen which has obviously influenced the strength of the final composite.

Compared to plain concrete (Atis, 1995), grouted macadams had approximately 25% of the strength of plain concrete at 28 days curing.

3. Conclusion

1. The strengths of the hot mix grouted macadam were predominantly influenced by the strength of the cementitious grout. For a fully hydrated composite, the strength of the grouted macadam was approximately 11% of the strength of the constituent hydrated cementitious grouts. As a general guideline, for all the grouted macadam mixtures investigated, by ignoring the relatively low strength porous asphalt skeletons, it was found that the strength of the hydrated composite could be expressed as 1.35 times the square root of the compressive strength of the hydrated cementitious slurry.

2. In general the compressive strength of hydrated cold mix grouted macadams were lower than those of hydrated hot mix grouted macadams due to the lower compressive strength of their respective cold mix porous asphalt skeletons. The rate of compressive strength development for the cold mix grouted macadams were higher than those of the hot mix grouted macadams, as a consequence of the cold mixture porous asphalt skeleton also developing strength during the curing process.

3. The compressive strengths of hydrated grouted macadams are more affected by the particle strengths of the aggregates used and the structure of the pores (size and interconnectivity), than the shear strength of their porous asphalt skeletons.
4. By carefully designing both the porous asphalt skeleton and the cementitious grouts, the compressive strengths of the grouted macadams produced in this investigation outperformed those of previously designed grouted macadams such as Densiphalt and resin modified pavements. In comparison to concrete, the compressive strengths of the grouted macadam produced in this investigation were approximately 25% of those of concrete.

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