Microscopy as a tool to investigate low strength concrete in new slip-form pavement

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INTRODUCTION

The objective of this study was to investigate the cause of lower than expected 28-day compressive strength for a newly placed slip-formed concrete pavement. Cores were drilled and examined from both low strength pavement lots and lots that met the 4000-psi specified strength. Since the same mix proportions and concrete constituents were reportedly used in the pavement construction, the cause of these marked differences in the compressive strengths among the lots was not clear.

The most commonly cited factors in reducing the compressive strength of a concrete include: high water to cementitious material ratio, excessive air content, improper mixing and poor consolidation, poor aggregate quality, poor aggregate-paste bond, and poorly formed cement paste in the interfacial region adjacent to the aggregate [1-3]. It is known that aggregate quality including physical properties and mineralogical compositions, and aggregate-paste bond are often listed as important factors influencing compressive strength of concrete [4,5]. The surface characteristics of aggregates and internal defects (cracks and porosity) of aggregates are also important factors affecting compressive strength of a concrete [4]. While all the factors listed above are potentially important, the quality of the interfacial transition zone (ITZ) often appears more important in lowering the compressive strength of concrete as the ITZ is known as a "weakest link of the chain "and thus considered as the strength-limiting phase in concrete [6]. Aggregate surface characteristics and air voids or portlandite clustering at or near the aggregate-paste interfaces are often cited factors influencing the paste-aggregate bond strength of a concrete.

It is reported that the microstructure of a rock in relation to weathering is the main feature controlling the physical and mechanical properties of the rocks. Weathering can cause a major change in the porosity and mineral soundness of the rocks by creating secondary minerals and defects [7] and by creating unsound weathering/alteration products [8]. Weathering occurs both in the initial environment of rock formation in geological time scale and in a secondary depositional environment after the rocks have moved to secondary formations (such as cobble, gravel, and sand deposits) by agents of erosion. Weathering of basaltic and andesitic volcanic rocks in the primary site of rock formation [8] and at the secondary site of deposition [9] were studied in eastern Australia and the western United States, respectively. In both studies, the main alteration products were different clay types (palagonite, saponite, smectite, halloysite and kaolinite). The specific composition of the clay depends upon the mineralogical composition of the initial rock forming minerals. The authors concluded that the rate of weathering of individual minerals is consistent with the well-known susceptibility series: glass ~ olivine > plagioclase > pyroxene > opaque minerals.

It is also known that clay minerals form in secondary sites such as alluvial and glacial deposits. Aggregate coatings can also affect how well cement paste adheres to the aggregate surface after mixing. Clay fines can bind to the aggregate by electrostatic forces, and many researchers suggest that these clay coatings can disrupt the aggregate-cement paste bond [10-13].

RESULTS OF MICROSCOPIC EXAMINATION

After a preliminary stereomicroscope examination of saw-cut concrete slab sections, we observed that the concrete in the slip-form pavement was made with a well-graded natural gravel coarse aggregate consisting mainly of basic and intermediate volcanic rocks. Some of these particles exhibited obvious gaps/cracks at paste-aggregate interfaces and also exhibited internal defects (crack/pores). Some of the basic and intermediate aggregate particles also contained locally unsound altered (secondary) minerals. For this reason, the focus of our study was on the aggregates and the ITZ. One hypothesis was that some aggregate surfaces might contain tightly adhered clay coatings that inhibit bonding with the paste thus compromising aggregate bond and strength of the newly placed concrete pavement. But we also saw a need to assess the quality of the aggregate as well.

Basic and intermediate volcanic aggregate particles in the concrete was estimated to be about 60 to 70% using the stereomicroscope observation of the lapped concrete sections and polarized light microscope (PLM) examination of thin sections. However, these constituents are relatively lower in the fine aggregate portion of the concrete. Petrographic analyses using stereomicroscopy and transmitted polarized light microscopy showed that the cause of low concrete strengths was related to the poor performance of some unsuitable (weathered and altered) coarse and fine aggregate particles used in the concrete. Some of the basic volcanic rocks (especially basalt and andesite) exhibited different degrees of weathering and alteration of the original rock forming minerals and the matrix which apparently have resulted in physical and mineralogical changes of these rocks which worked against the performance of the aggregate particles in the concrete. Stereomicroscopy and transmitted light optical thin section analyses showed that some of the weathered and altered basalt and andesite coarse and fine aggregate particles exhibited gaps/cracks around the particles causing poor bonding with the paste (Figures 1 and 2). This is attributed to the presence of thin clay-like weathering rinds/rims on the external surfaces of the aggregates (Figure 1).

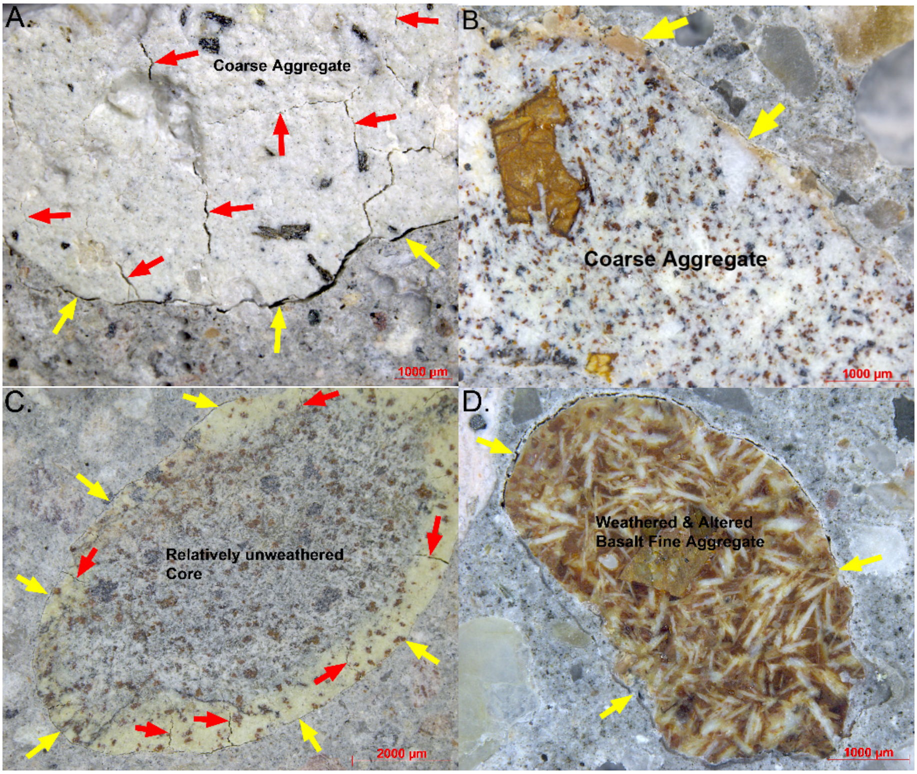

Figure 1: Stereomicroscope photomicrographs of selective areas of saw-cut surfaces showing gaps/cracks around volcanic coarse (A & B) and fine (C & D) aggregate particles (shown by yellow arrows.) Note the basalt fine aggregate (C) with a weathered and altered rim (moderate yellow) and with gaps/cracks at the interface with the paste and internal microcracks within the weathered rim oriented approximately perpendicular to the rim. Note (A) the internal cracks in the volcanic coarse aggregate.

Transmitted light examination of thin sections showed that most of the observed rinds around weathered volcanic aggregate particles have a distinct brownish muddy color on some particles (perhaps palagonite/smectite with iron oxides/hydroxides) (Figure 2 a, b & c), more of a clear transition in some other particles, from moderately weathered interior part of the rock into more intensely weathered and altered external rim of the aggregate (example, Figure 2d). Figure 2c portrays an example of a weathered particle exhibited three zones: less weathered interior, strongly weathered front, and thin brown clayey rind surrounding the strongly weathered front. PLM examination confirmed that most of the observed gaps/cracks occur at the interfaces of the rinds and cement paste (example, Figures 2a, c, & d) and sometimes both through the rind and rind-paste interface (example, Figure 2b). The formation of gaps/cracks due to the lack of good bonding between some of the weathered and altered basic and intermediate volcanic rocks and the cementitious paste appears to be the primary cause of the low compressive strength.

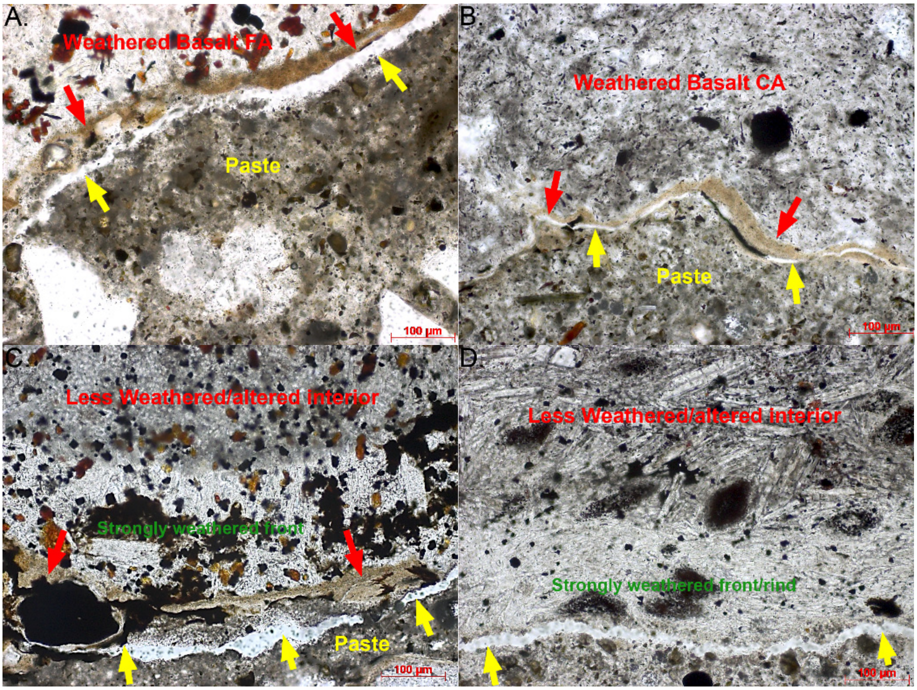

Figure 2: Transmitted light thin section photomicrographs made from selective represntative areas of the concrete showing aggregate particles with gaps/cracks at the interfaces with the paste. Gaps/cracks (shown by yellow arrows in all four images) formed at the interfaces of weathering rinds and the paste (red arrows in all but the lower right image) mark prevalent weathering rinds developed on the outer surface of weathered basalt coarse and fine aggregate particles. Note the strongly weathered front in what appears to be trachytic basalt in which the plagioclase feldspar laths were decomposed and altered into a fine-grained clayey mass (lower right image).

PLM examination also showed that some of the weathered basic and intermediate volcanic aggregate particles contain two or more than two alteration minerals including clay; clay in association with what appears to be palagonite (alteration product of the glass matrix); and other miscellaneous secondary alteration minerals (including chlorite, perhaps zeolite, and goethite). The alteration minerals occur as a replacement for the original ferromagnesian minerals (particularly olivine and pyroxene) and phase(s) in the matrix, and filling amygdales and cracks within these rocks. The alteration minerals, especially the ones replacing the ferromagnesian primary minerals exhibited microcracks associated with the alteration minerals (Figure 3). Also, a few weathered volcanic aggregate particles exhibited internal cracks initiated within altered and weathered matrix (Figures 1a & 3a). These cracks, and the cracks observed in the secondary minerals in conjunction with the relatively softer nature of these alteration products may have also contributed to the overall reduction of the strength of the concrete by reducing the strength of individual aggregate particles.

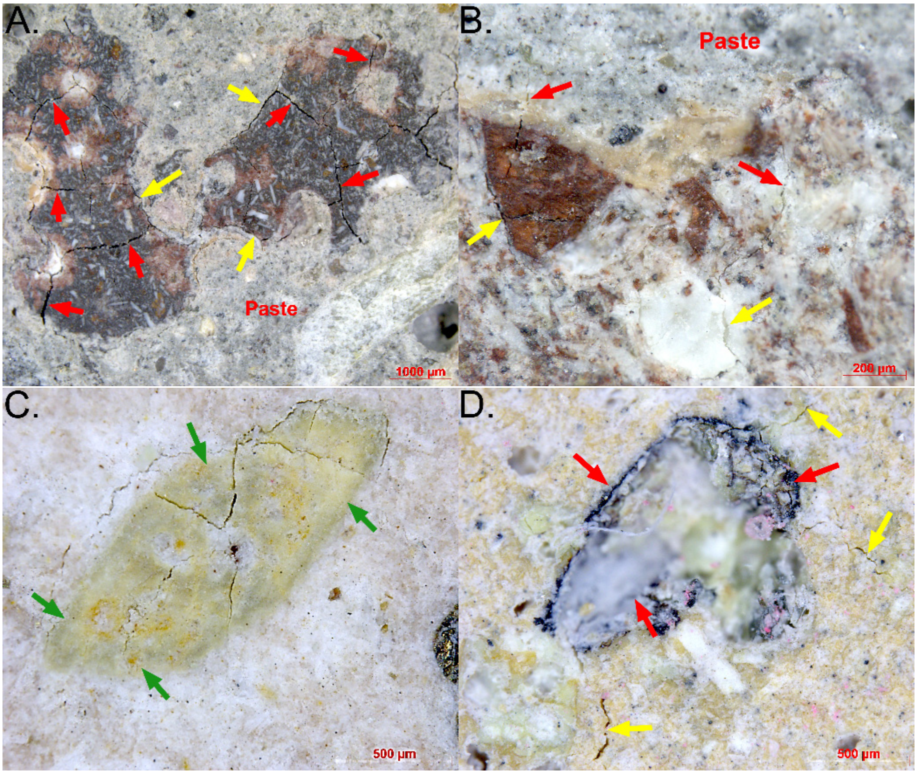

Figure. 3 Stereomicroscope photomicrographs of selected areas of saw-cut surfaces showing intensely weathered and altered basalt aggregate particles. A- Completely altered, friable basalt fine aggregate showing a gap/crack at the interface (shown by yellow arrows) as well internal cracks (red arrows); B- Microcracks extended from altered ferromagnesian minerals (shown by yellow arrows) into the adjacent paste (shown byb red arrows); C- Close-up of a weathered volcanic coarse aggregate in which the original volcanic phenocryst (shown by green arrows) was replaced by what appears to be volumetrically unstable alteration products (chlorite and perhaps zeolite?) associated with microcracks; D- Completely altered, what appears to be an olivine phenocryst (shown by red arrows) with microcracks extended from it into the matrix of the rock (shown by yellow arrows). Iron oxide/hydroxide associated with green alteration minerals (chlorite mixed with zeolite) appear replaced the original phenocryst.

One likely phenomenon which may happen with alteration minerals, particularly clay minerals, at the rinds as well as within some of the weathered and altered aggregate particles is that particles may have absorbed water during aggregate processing or during mixing and then upon drying in the stockpile or later in the concrete, may have resulted in the observed shrinkage-like microcracks within the aggregates and may also have contributed to the pulling away of these aggregates from the paste creating gaps at the interfaces.

The reason why concrete in some pavement lots met the compressive strength requirements (see Table 1 below) is explained by the observed lack of significant amounts of weathered aggregate particles in the good concrete. This suggests aggregate from a different location or perhaps aggregate from a relatively deeper weathering horizon in the sand and gravel source was used in areas of the pavement that met the designed strength. Previous studies stated that weathering-rind thickness appears to progressively decrease with depth in a weathering profile (from the B horizon downward to the C horizon) [9]. This study also stated that rock particles from C horizons have thinner weathering rinds than B horizons. So, the reason for the good performance in some areas was the scarcity of the strongly weathered basalt and andesite particles with weathering rinds; and, thus, there was an absence of significant gaps and/cracks at the aggregate interfaces with the paste.

Table 1. Core Sample IDs, the 28 days required strength and the actual measured strength

Sample ID	28-day required strength (psi)	Actual strength (psi)
Core 1	4000	>4000
Core 15	4000	3560
Core 16	4000	3490
Core 19	4000	3550
Core 24	4000	3420
Core 27	4000	3180

CONCLUSIONS

Based upon forensic petrographic analyses, the following conclusions are drawn.

1. The root cause of the lower than expected compressive strengths of the newly placed concrete pavement appears primarily attributed to the lack of good bonding between some strongly weathered basic and intermediate volcanic aggregate particles and the cementitious paste due to the presence of thin weathering rinds along the rims of these aggregates. Due to this reason, some weathered and altered basalt and andesite coarse and fine aggregates exhibited gaps/cracks at the interfaces with the paste.

2. The reason why concrete from a few lots met the expected compressive strengths but not the concrete from other lots may be explained by the observed scarcity of strongly weathered basalt and andesite with weathering rinds and thus absence of significant gaps and/cracks at the interfaces with the paste.

3. The presence of what appears to be excessive internal cracks and microcracks in some of the weathered and altered basic and intermediate volcanic rocks, observed drying-shrinkage-like localized microcracks associated with secondary alteration minerals that replaced the original ferromagnesian minerals and the groundmass/matrix compounded with the very soft nature of some of these secondary alteration minerals, may have also contributed to the lower strength of the concrete by reducing the strength of these individual particles.

4. The presence of pseudomorph crystals of the original rock forming minerals suggests replacement of the primary minerals by secondary minerals during initial geological hydrothermal alteration. In some aggregate particles, there is evidence suggesting further alteration of the initial alteration minerals by the long-term weathering processes resulting in more complex alteration products. In a few cases, the prolonged weathering process resulted in the formation of weathered and friable/unsound aggregate particles (example, Figure 3a).

5. No other mechanism(s) of deleterious reactions involving the aggregate and/or cement or any other unusual features were observed in the analyzed samples.

LESSONS LEARNED & RECOMMENDATION

What we learned from this case study is that it is a good practice to test each aggregate source for deleterious materials and overall quality of the aggregate periodically. Aggregate testing such as wet attritioning tests for both fine and coarse aggregates – such as the Micro-Deval test, California Durability Index, Sand Equivalent, and/or Cleanness Value can be run. Other recommended tests for quality include: absorption limits; freeze-thaw; sulfate soundness, as well as petrography of the source aggregate. The aggregate quality and amount of potentially deleterious material may vary depending up where the aggregate is mined in a deposit/quarry. If there is no other way to remove and/or clean the outer weathered rinds/surfaces of aggregates, crushing of the gravels followed by washing and attrition processing of both fine and coarse aggregate to remove weak/friable materials and expose freshly fractured surfaces which are more conducive to tight paste-aggregate bond and quality concrete pavements.

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