APPLICATIONS OF HIGH PERFORMANCE BINDER-TREATED MATERIALS

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Abstract

Binder treated materials such as ANCORBOND® and ANCORDENSE® increase the performance characteristics of ferrous powder premixes and P/M parts. This paper will discuss the various characteristics of binder treated premixes and their potential applications. A review of the mechanical properties of ANCORDENSE materials will be presented.

Introduction

The applications for powder metallurgy (P/M) are becoming more numerous and more complexes with ever-increasing demands on the mechanical properties of the resultant parts. This growth in the usage of ferrous P/M applications can be traced to advances in raw materials (including high compressibility iron powder, molybdenum prealloyed powders, and diffusion alloyed powders), advances in compacting and sintering equipment, along with advances in premixing technology. These new powders and processing offer both the fabricator and user of P/M parts greater flexibility in specifying and achieving mechanical properties at part densities ranging from 6.6 g/cm^3 to 100% of pore-free density (achieved via powder forging techniques).

The performance of a P/M part can be specified by the density, microstructure, and composition of the finished component (Ref. 1). Part density or controlled porosity is unique to P/M, and it allows the possibility of self' lubrication, reduced mass, and the ability to selectively density critical sections of the part to meet specific part performance requirements. Density significantly influences the overall part performance as measured by the yield and tensile strengths, ductility, impact toughness, and fatigue resistance. Increasing the part density is beneficial to all mechanical properties and has become the development focus of many new P/M part applications. However, it is important to recognize that the alloy composition of the P/M part also plays a critical role in the mechanical properties through solid solution strengthening of the iron in addition to affecting the heat treat response of the P/M part. Sinter hardening is an example of how the alloy composition of a P/M part can be varied to produce an as sintered part that has in excess of 50% martensite by utilizing accelerated furnace cooling (Ref. 2). P/M parts produced by sintering-hardening possess excellent surface wear characteristics; however, these parts have reduced mechanical properties compared with quench-hardened materials.

The inter-relationship of composition and microstructure exists within wrought steels; P/M has the added capability of intentionally creating heterogeneous microstructures that are not possible in wrought steels. The heterogeneous microstructure can be controlled to incorporate hard phases within a relatively soft matrix to promote enhanced wear while maintaining a ductile matrix material. Alternatively, a heterogeneous microstructure can be utilized to incorporate soft crack arresting particles in a hardened steel component. Thus, the relationship of density, microstructure, and composition is one that can be exploited by the design engineer to maximize benefits of the P/M process. With these advances in materials and the ever increasing demands on P/M parts, it is necessary to ensure that the premix composition remains consistent from part to part within a lot and from lot to lot. This necessitates that premix segregation and demixing be minimized or eliminated to insure the required part response. Additionally, the premix must be free flowing to promote improved die fill and press performance.

Binder treatment of ferrous powder premixes represents a significant advancement in premixing technology that minimizes the segregation, demixing, and potentially non-flow conditions that are inherent with particulate materials consisting of differing particle sizes and particle densities (Ref. 3). This technology is a synergy of powder metallurgical processes with polymer science and chemical processing to disperse the polymer to achieve the desired bonding characteristics. The first North American commercial application of binder treated iron powder premixes was the introduction of ANCORBOND premix technology in 1988 (Ref. 3). In this initial work, the ANCORBOND process demonstrated improved powder flow, improved die fill, and reduced part to part variability in the green and sintered conditions. These improvements resulted from the bonding of the fine particle additions to the iron powder. This bonding has the twofold benefit of increased uniformity of the fine alloy addition and the elimination of dusting during part manufacturing.

Reduced dusting represents a significant improvement in housekeeping and increased operator comfort. Figure 1 presents the effects of ANCORBOND processing on the respirable dust within the workplace. The data indicates that binder treated premix reduces the background dust levels in the plant area and immediate press area to a level undetectable using National Institute for Occupational Safety and Health (NIOSH) Methods 0600 and 7300 (Ref. 4). In the space within the die area, the reduction of respirable dust is tenfold. This reduced dusting contributes to greater alloy recovery throughout the entire P/M process from premix production to final part pressing.

The intent of this paper is to review the binder treatment of ferrous powder premixes. It is noteworthy that ANCORBOND is a family of engineered materials that were designed to satisfy a broad range of part applications. Proper use of ANCORBOND technology requires understanding of the process and the potential applications.

ANCORBOND Technology For Part Densities up to 7.1 g/cm^3

ANCORBOND premixing technology encompasses a family of engineered materials that satisfy the demands of the P/M industry for enhanced flow, enhanced densification, reduced segregation, greater green strength, and reduced part to part variability. When introduced in 1988, ANCORBOND was designed primarily to produce enhanced flow and die fill while simultaneously giving reduced dusting and reduced part to part variability. This original binder treated premix concept utilized a binder in addition to the added premix lubricant. That is, the lubricant level remained constant with the binder as an additional additive. The binder added was an additional Low specific density additive that reduced the pore-free density (PFD) of the premix. Consequently, the limitation of this first generation ANCORBOND material was a maximum green density of 6.9 g/cm^3. Attempts to compact premixes of this initial ANCORBOND technology above densities of 6.9 g/cm^3 led to overpressing of the premix and the potential for microlaminations within the compacted part. However, it is significant that this initial material satisfied the market need for improved flow, increased press rates (up to 25%), and reduced part to part variability (Ref. 5). The first generation ANCORBOND premixes possessed higher apparent density (AD) relative to that of the regular premix, which were both an advantage and a disadvantage. The higher AD allowed longer parts to be made with less die fill; however, retrofitting of existing premixes that were utilized in fixed fill tooling was not possible.

With the introduction of the first generation ANCORBOND, market trends in the P/M industry indicated that P/M part densities were increasing and the future for P/M was in parts that displaced steel forging or high strength castings. These higher mechanical property requirements could only be satisfied by P/M parts with a density above 6.9 g/cm^3. Figure 2 shows the growth of the P/M industry and how this growth is projected in high strength, high density applications. The obvious trend for higher part densities limited the potential for the original ANCORBOND technology in these new high-density market opportunities.

To address the need for high part densities, it became necessary to lower the total amount of lubricant and binder added to the premix. The optimal situation was to utilize a polymeric binder that had both bonding and lubricating characteristics. Developmental work at Hoeganaes Corporation in the late 1980's produced a lubricant-binder system that reduced the total organic content of the premix enabling part densities up to 7.1 g/cm^3. The benefits of this second generation ANCORBOND are a parity of green density with conventional mixes with improved green strengths and lower ejection forces. Additionally, this second generation material exhibited equivalent compacted densities at Low to moderate pressures but showed increased green densities of up to 0.1 g/cm^3 at compacting pressures in the range of 40 to 50 tsi (Ref. 6). The second generation binder treated premixes exhibited the same higher AD compared with a non-bonded material but continuous improvement in the processing enabled retrofit premixes to be formulated that can be utilized in existing fixed fill dies. The benefits of increased press rates, enhanced powder flow, and increased material consistency that were inherent in the initial ANCORBOND are present in this second generation material, with the additional benefit of increased green densities of up to 7.1 g/cm^3.

Pore-Free Density (PFD)

To understand the effect that premix additives have on the maximum green density attainable, it is useful to review the concept of pore-free density (PFD). PFD is defined as the density of a green compact in which all the interparticle porosity is eliminated (Ref. 7). This PFD can be calculated from the specific density and percentage of each additive in the premix. The calculation for pore-free density is given as equation 1,

PFD = (1 / ($\sum$ (% element in premix / specific density of additive) eq 1

In which the percentage of each element is the weight percentage used and is expressed a decimal. Once the pore-free density is calculated, a practical upper limit of maximum green density is 98% of the calculated PFD. The density of several common ferrous powders and typical premix additives are listed in Table 1. Additions of materials with densities higher than the base iron will increase the pore-free density, while additions of materials with lower specific densities (lubricants and graphite) will lower the pore-free density.

Table 1
Density of Several Common Premix Additions
(Measured with a pycnometer)

Material	Specific Density g/cm^3
Ancorstee11000B	7.841
Ancorsteel 4600V	7.844
Distaloy AE	7.896
Atomized Copper	8.047
Inco Nickel Powder type 123	8.846
Graphite	2.295
Lubricants	0.90 to 1.15

To achieve P/M part densities above 7.1 g/cm^3, the traditional approach in P/M was to utilize double pressing and double sintering (DP/DS). This approach although useful and practical for many P/M parts has the disadvantage of higher unit part cost because of the extra processing steps plus it is often difficult to DP/DS multi-level shapes. The trend to higher part densities and lower cost led to the introduction of ANCORDENSE processing.

ANCORDENSE

In ANCORDENSE processing, the powder and tooling are preheated to 130°C to 150°C (265°F to 300°F) temperature results in higher green and sintered densities (Ref. 7). The actual concept of warm compaction was not new; rather, it has been known for some time that compaction at elevated temperature reduces the compressive yield strength of the iron powder by approximately 30% (Ref. 8). However, the early experimental work utilized die-wall lubrication, which at that time was not practical for mass production of P/M parts. What was needed was a lubricant and binder system that could withstand the higher compaction temperature and provide the required lubricating qualities. The ANCORDENSE process successfully satisfied the higher temperature lubricating and binder criteria necessary to commercialize warm compaction. Experimental work demonstrated that compaction at 150°C (300°F) reduces the amount of interparticle lubricant while simultaneously increasing the amount of lubricant reaching the die-part interface (Ref. 9). This redistribution of the lubricant has the two-fold benefit of increasing the green density but reducing the ejection forces by 25% to 33% (Ref. 7). This enhanced lubricity implies that lower amounts of lubricant are necessary (typically 0.60w/o lubricant for warm compaction compared with 0.75w/o in conventional compaction) which again contributes to the attainment of higher green and sintered densities.

Additional benefits of the ANCORDENSE process are significantly increased green strengths of up to 4000 psi that enables green machining of P/M parts (Ref. 10). The reduced compressive yield strength of the powders at 150°C (300°F) also gives significantly higher compressibility at lower compacting pressures. Experimental work has shown that a 0.25 g/cm^3 increase in green density is possible with compaction pressures as Low as 30 tsi (Ref. 7). At 50 tsi. the incremental increase in green density is 0.10 to 0.15 g/cm^3. The magnitude of the increase is dependent upon the alloy system used and the part geometry. One significant benefit of ANCORDENSE processing is the greater uniformity in green density throughout the compacted part when compared with conventional compaction techniques (Ref. 11).

This transition to part densities up to 7.4 g/cm^3 accentuates the need for a high performance binder system that will give enhance part and press performance. Experimental work done at Hoeganaes Corporation demonstrated that a non-binder treated premix heated to 140°C (285°F) gave significantly higher variability relative to a binder treated premix. This higher variability potentially results in excessive tooling loads with the possibility for tool breakage. Production experience with the ANCORDENSE process demonstrated the process is capable of giving part to part variability of +/- 0.5w/o if the operating temperature is controlled to +/- 2.5°C (5°F). Equal press speeds were achieved with the warm compaction process compared with conventional compaction. The limiting feature in part production is the capacity of the powder heating system and the part mass.

Table 2 summarizes the as sintered mechanical properties of various warm compacted premix compositions. Sintered tensile properties are dependent upon the alloy composition and pressed density. It is possible to achieve single press/single sinter yield strengths of ~ 80,000 psi with tensile strengths in excess of 110,000 psi. This processing is applicable to all iron and Low alloy powder compositions. The magnitude of the increase in sintered density will depend upon the material system and subsequent part processing. Premixes containing copper additions exhibit growth during the sintering process and this growth negate the beneficial effects of the warm compaction processing. Consequently, copper containing premixes are not considered ideal candidates for warm compaction (Ref. 12).

Rotating bending fatigue testing was performed on a variety of warm compacted materials in both the as sintered and heat treated conditions; Table 3 summarizes the available data (Ref. 13). As expected, increasing the density increased the fatigue endurance limit; however, higher temperature sintering did not consistently improve the fatigue endurance limit. Reviewing Table 3, it is observed that no generalized correlation exists between the fatigue endurance limit and the tensile strength of P/M materials. It is recommended that fabricators use available data when specifying the fatigue endurance limit of P/M components.

In experimental work performed by Donaldson, et al, warm compacted P/M parts were presintered at 1600°F (8700F) and subsequently repressed at pressure up to 50 tsi at room temperature (Ref. 14, 15). Following repressing, the parts were then sintered at either 1120°C (2050°F) or 1260°C (2300°F), resulting in sintered densities ranging from 7.5 to 7.6 g/cm^3. These higher densities produced approximately a 15% improvement in the transverse rupture strengths but more importantly resulted in a 50% to 80% improvement in the impact energy when compared with the 7.4 g/cm^3 density level. This study demonstrated the potential for significant improvement in the mechanical properties of P/M materials via DP/DS of a warm compacted component. The resultant mechanical properties of such parts are equivalent to the properties of ductile cast irons and machined carbon steel forgings.

Future Direction for ANCORBOND Premixes

The future direction for ANCORBOND premixes for the P/M industry is to replace high strength steel castings and steel forgings. The successful commercialization of the ANCORDENSE turbine hub demonstrated that a high density P/M part can replace a steel forging and provide equal component performance with a substantial part cost savings (Ref. 16). Figure 3 shows the mechanical properties of selected cast and wrought steel materials compared with a diffusion alloyed powder and a hybrid material based on a prealloyed molybdenum steel powder. It is interesting that the yield and tensile strengths of the ANCORDENSE material sintered to a nominal density of 7.3 g/cm^3 are almost equivalent to the properties of the AISI 8620 material and superior to the ductile iron casting and powder forged materials. Thus purely from a strength standpoint the ANCORDENSE materials are suitable alternatives. One aspect that Figure

3 does not show is the fact that the ANCORDENSE materials have Low elongation and impact energy relative to the competing materials. This deficiency can only be overcome by increasing the part density.

Methods to increase the part density of ANCORDENSE materials include a DP/DS of this material to increase the part density to 7.5 g/cm^3 and above. The drawback to this processing route is the added cost of the DP/DS process may make the final P/M part non-competitive from an economic perspective. This will not be true in all cases but is necessary to consider this fact for these potential applications.

Another method to increase the part density can be found by reviewing the concept of PFD; specifically, reducing the lubricant addition from 0.75w/o to 0.60w/o as done in ANCORDENSE resulted in a 0.15 to 0.25 g/cm^3 increase in green and sintered density. It is logical to expect that further reductions in the lubricant level will give additional benefits in the green and sintered densities. Experimental work was performed in which the lubricant level of a conventional premix was decreased incrementally from 0.75w/o to 0.30w/o. Figure 4 presents the results of this effort.

Reducing the lubricant level to 0.3w/o resulted in a 0.13-g/cm^3 increase in green density on a TRS bar (0.5 inch tall). However, the ejection pressure measured on the same TRS bar almost doubled to 7 tsi from - 4 tsi (at 0.75w/0 lubricant). This work suggests that reduced levels of lubricant can increase the density of a part to the level found with ANCORDENSE processing; however, the resulting increase in stripping pressure and potential scoring of the die set are issues that must be resolved. It has been suggested that die-wall lubrication can help alleviate this problem (Ref. 17). However, the possibility for inadequate spray can cause excessive stripping pressures and die scoring. An engineered solution to this problem is the merging of technologies; in particular, an ANCORDENSE premix with reduced levels of lubricant coupled with a die-wall spray technology. This has the potential to achieve as pressed densities of nearly 7.5 g/cm^3 (depending upon the PFD of the premix). Several opportunities are under investigation to commercialize these higher green and sintered densities.

The trend in P/M parts is for greater complexity with higher levels of mechanical properties and consistent part to part dimensional accuracy. Achieving this goal via single press and single sinter techniques will require innovative solutions to lubricant technology and part compaction. The use of a binder treated material is imperative to ensure consistent dispersion of the lubricant and fine alloy additives. Without this consistent distribution of the alloying particles, the enhanced dimensional control required and the high level of mechanical properties will not be achieved.

Summary

ANCORBOND premixing technology encompasses a family of engineered materials giving enhanced flow, die fill and apparent density that can be used in density ranges up to 7.4 g/cm^3.

In addition to the enhanced powder premix properties, the resulting green and sintered part shows reduced variability in alloy segregation, part to part weight variability, and dimensional control. Since its introduction in 1988, ANCORBOND has been continually improved to addressed the needs of the P/M market. Specifically, the apparent density can now be controlled to enable retrofitting of existing mix apparent densities so that existing tooling can be used. Additionally, with the P/M industry producing more complex higher density parts, these needs can be satisfied by the ANCORDENSE technology.

Future developments planned for this technology include the development of premixes containing still lower lubricant amounts enabling single press/single sinter part densities of 7.5 g/cm^3 and above. The advent of this will give the P/M industry additional tools to make high performance parts and continue the growth of this industry.

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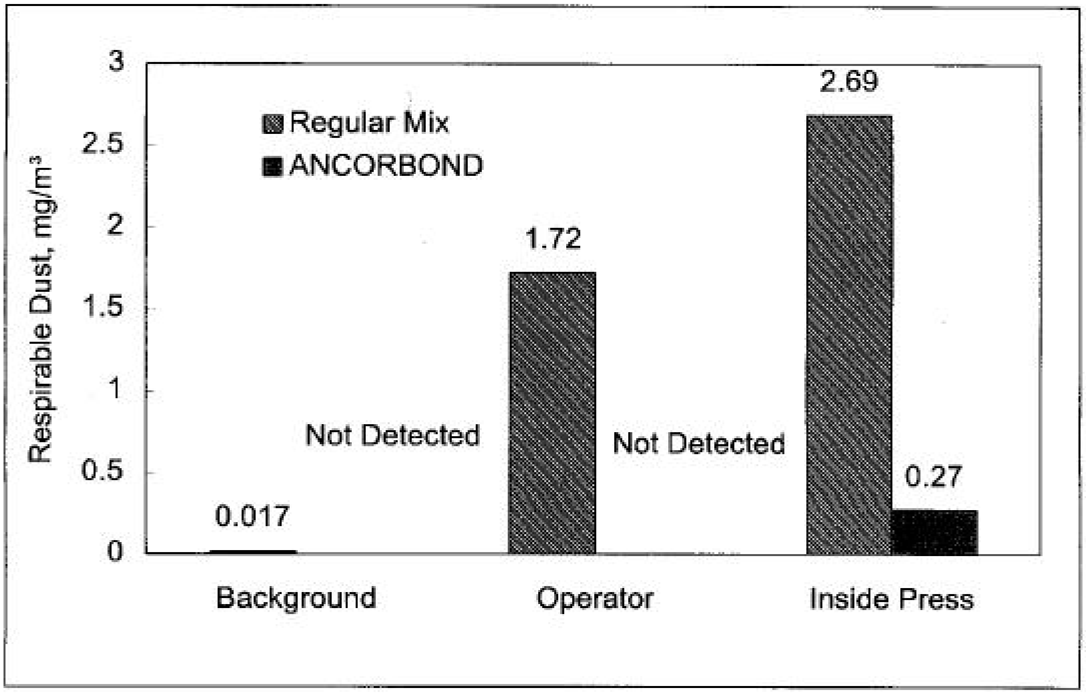

Figure 1: Respirable dust in work area for a conventional premix and ANCORBOND premix.

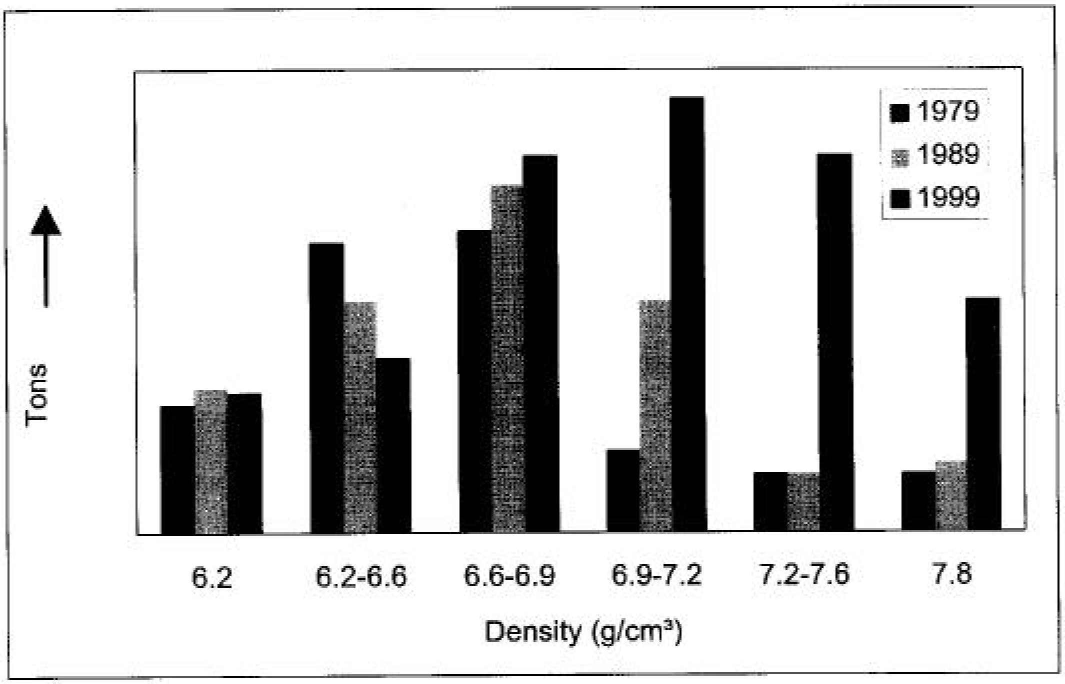

Figure 2: Industry trends of part density

Table 2
As-Sintered Tensile Properties of Warm Compacted P/M Materials, Sintered at 2050°F (1120°C)

Composition	Sintered Density (g/cm^3)	0.2% Offset Yield Strength psi (MPa)	Tensile Strength psi (MPa)	Elong. %	Apparent Hardness HRB
FL-4405	7.37	40,000 (273)	69,000 (471)	3.5	77
FLN 2-4405	7.44	65,000 (444)	92,000 (628)	2.8	87
FL-4205	7.24	61,000 (417)	74,000 (506)	1.7	81
FLN2-4905	7.40	78,000 (533)	105,000 (718)	1.3	93
FD-0405	7.25	62,000 (425)	117,000 (800)	2.6	97
Iron+0.45w/o Phosphorus	7.39	39,000 (267)	62,000 (422)	25	67
FN-0205	7.37	39,000 (267)	66,000 (452)	3.5	79

Table 3
Fatigue Data of Warm Compacted Ferrous Materials

Material	Sintering Temp. (°F/°C)	Heat Treat	Density (g/cm³)	50% FEL (10³psi / MPa)	99% FEL (10³psi / MPa)	Tensile Strength (10³psi / MPa)
Iron + 0.45 w/o P	2050/1120	No	7.23 7.40	30 / 207 32.7 / 225	26.8 / 185 28.6 / 197	53 / 365 58 / 403
Iron+0.45w/o P	2300/1260	No	7.33 7.50	31.4 / 216 37.7 / 260	29.7 / 210 34 / 234	59 / 403 69 / 476
FC-0208	2050/1120	No	7.07 7.17	33.9 / 234 35.3 / 243	25.4 / 175 28.0 / 193	86 / 596 90 / 621
FD-4805	2050/1120	No	7.19 7.32	33.3 / 230 35.3 / 242	26.3 / 181 27.8 / 192	103 / 710 115 / 798
FD-4805	2300/1260	No	7.26 7.37	31.5 / 217 32.9 / 227	24.9 / 172 26.9 / 185	118 / 814 134 / 925
FD-4805	2050/1120	Yes	7.20 7.32	57.9 / 399 59.3 / 409	46.0 / 317 48.1 / 332	181/ 249 193/1327
FLN2-4905	2050/1120	No	7.18 7.34	33.8 / 233 38.0 / 262	27.4 / 189 35.0 / 241	93 / 641 101 / 693
FLN2-4905	2300/1260	No	7.21 7.37	30.0 / 207 37.1 / 256	24.0 / 165 29.2 / 201	95 / 652 103 / 710
FLN2-4405	2050/1120	No	7.31	36.7 / 253	32.2 / 222	91 / 632
FLN2-4405	2300/1260	No	7.35	35.8 / 247	31.7 / 219	98 / 672
FLN2-4405	2350/1290	No	7.20	34.6 / 239	32.9 / 227	90 / 621
Ancorsteel 41AB	2350/1290	No	7.16 7.27	35.1 / 242 39.2 / 270	30.4 / 210 34.0 / 234	124 / 856 133 / 917
Ancorsteel 41AB	2350/1290	Yes	7.16 7.28	58.5 / 403 65.1 / 449	51.2 / 353 59.4 / 410	176 / 1211 196 / 1349
FN-0250	2050/1120	Yes	7.23	45.8 / 316	40.1 / 276	176 / 1193
FL-4405	2050/1120	Yes	7.17 7.30	47.9 / 330 48.8 / 336	41.1 / 283 40.4 / 279	164 / 1131 167 / 1151
FD-0205	2050/1120	Yes	7.19 7.29	53.4 / 368 54.2 / 374	45.7 / 315 45.9 / 316	173 / 1192 189 / 1303

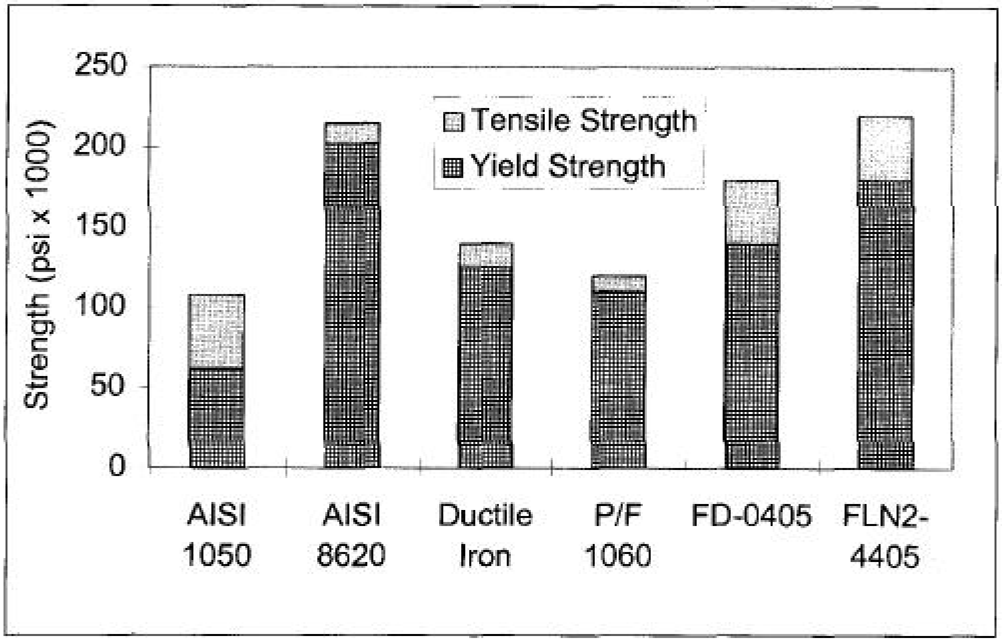

Figure 3: Mechanical properties of wrought and ANCORDENSE materials in heated treated condition.

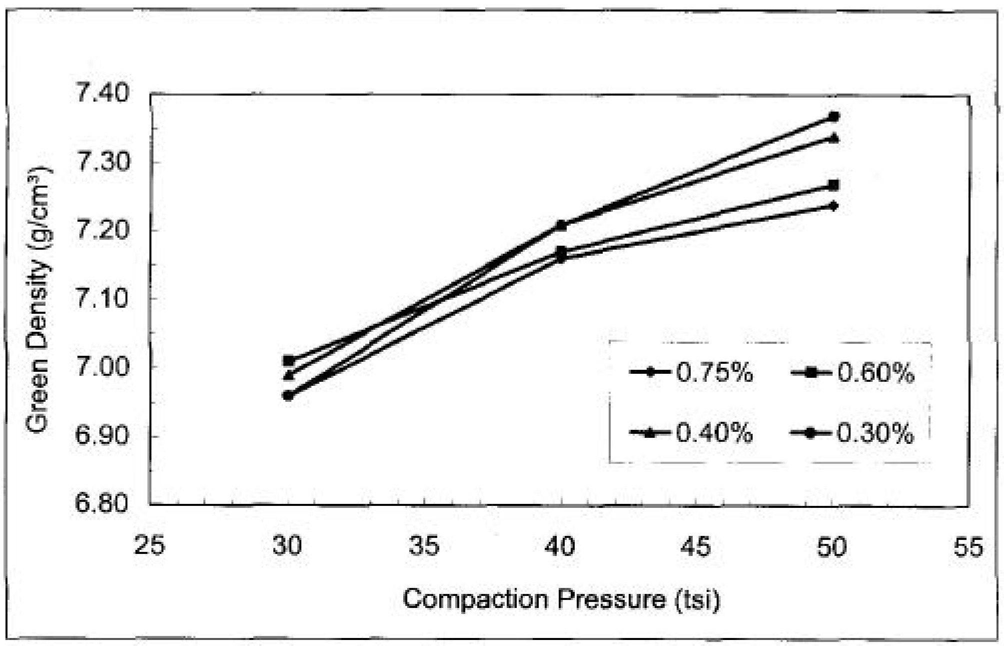

Figure 4: Effects of reduced lubricant levels on the green density of conventionally compacted premixes. The lubricant used was Acrawax.

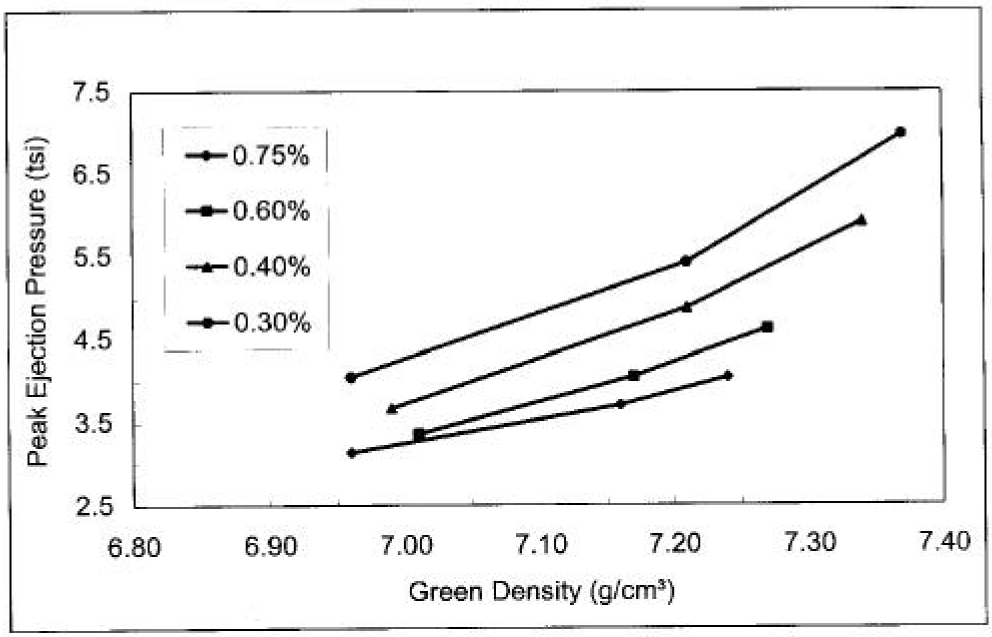

Figure 5: Effects of reduced lubricant levels on the ejection forces of conventionally compacted materials. The lubricant used was Acrawax.